A Systems Engineering Approach to Integrated Structural Health Monitoring for Aging Aircraft

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Abstract

The United States Air Force and many of its Coalition partners have extended the original service life of some of their aging aircraft due to fiscal constraints. This life extension often requires increased periodic and in-depth inspections, increasing maintenance costs and resulting in longer periods of aircraft downtime. An integrated structural health monitoring system (ISHMS) for aging aircraft may reduce the current inspection burden, and thus decrease costs and system downtime. This thesis developed a generic systems engineering process to describe the system definition for an ISHMS installed on a non-specific aging aircraft. The system definition developed in this thesis followed the Vee Model for systems development and serves as a starting point for future research and/or development efforts in this field. User analysis, user requirements, system requirements, and some Department of Defense Architecture Framework system architectures formed the basis for the generic systems engineering process presented. Furthermore, mathematical simulations compared the failure rate and number of inspections for a scenario *without* an ISHMS to a scenario *with* an ISHMS. This simplified analysis demonstrated that a structural health monitoring system for aging aircraft may have promising benefits with respect to both safety improvements and decreased maintenance costs.

Acknowledgements

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Figure 1: Thesis Group Photo In Front of YA-37A at the National Museum of the Air Force

Table of Contents

Page

List of Figures

Figure Page

List of Tables

List of Abbreviations

A Systems Engineering Approach to

Integrated Structural Health Monitoring

for Aging Aircraft

I. Introduction

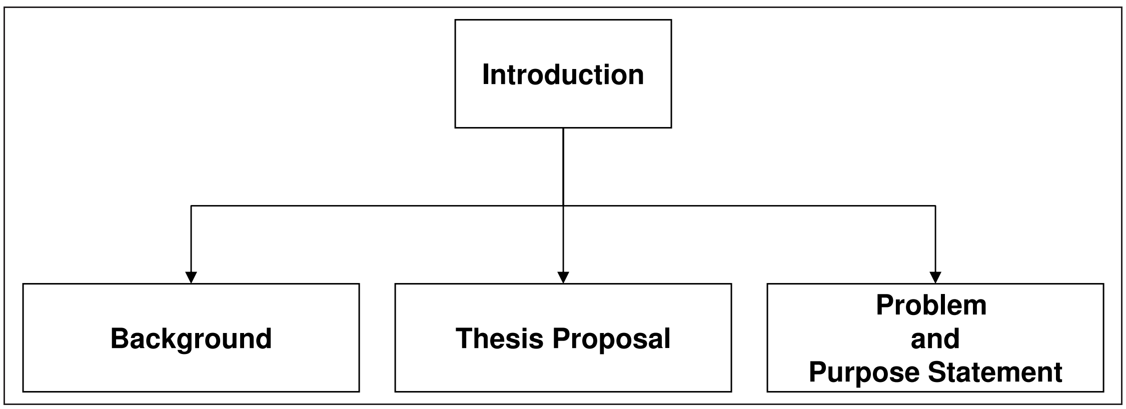

Figure 1.1: Chapter 1 Decomposition

This chapter (Figure 1.1) introduces the background to the request from the Office of the Undersecretary of the Air Force for International Affairs (SAF/IA) to develop a systems engineering (SE) approach for an integrated structural health monitoring system (ISHMS) for the Coalition Air Forces' (CAF) aging aircraft. Chapter 1 also addresses the problem statement and the purpose of this thesis. In addition, it states the reason this problem was selected and briefly describes how this problem was solved.

1.1 Background

The United States Air Force (USAF) and many of its Coalition partners have extended the original service life of some of their aging aircraft due to limited defense

budgets. However, this service-life extension often requires additional expensive, periodic, and in-depth inspections, resulting in the need to ground aircraft for long periods of time. The main purpose of these inspections is to preserve safety-of-flight (SOF), with emphasis placed on maintaining the aircrafts' structural integrity. Despite the relative success of these rigorous inspections, the aging aircraft community is in dire need of a more efficient way of monitoring and maintaining the SOF of their fleet. For example, the USAF has developed an integrated monitoring system on newer aircraft to help screen the aircraft's structural health, allowing the required maintenance inspection criteria to be tailored to each specific aircraft. As a result, this tailored inspection criteria has reduced the current inspection burden, decreasing costs, and system downtime.

Since trends have revealed a pattern of operating military aircraft beyond the original design life, there is a distinct need for a type of ISHMS that can be used not only on newer aircraft that have not reached the end of their service life, but also on aging aircraft. "Structural health monitoring refers to the use of in-situ, non-destructive sensing and analysis of structural characteristics for the purpose of detecting changes that may indicate damage or degradation [40]."

1.2 Thesis Proposal

The CAF currently flies many of its A-37 aircraft past the original service life and the rest of the A-37 fleet will soon exceed the service life. As a result, the CAF is experiencing significant A-37 aircraft (Figure 1.2) downtime (4 - 6 months) due to required structural inspections every 300-flight hours [59]. This situation was the original driving force behind the thesis proposal because the CAF A-37 fleet was considered a suitable candidate for demonstrating the feasibility of an ISHMS for an aging aircraft. Moreover, the CAF has expressed interest in and agreed to support future efforts in this area.

Figure 1.2: A-37 Photo [39]

1.3 Problem and Purpose Statement

The problem the thesis team faced is that a systems engineering approach has not been applied to the development and implementation of a cost-effective, near real-time, integrated structural health monitoring system on aircraft that did not have such a system in place. The CAF needs this type of system in order to continue the use of their A-37 aircraft beyond the designed service life while maintaining SOF.

The purpose of this thesis is two-fold. First, this thesis provides an SE process to help identify the top-level operational concept and stakeholder requirements of an ISHMS for a generic aging aircraft. In creating this SE process, the thesis team wore two hats, that of the user and of the systems engineer. The methodology for the SE process generally followed the systems engineering Vee Model (Figure 1.3). The thesis team created baseline products to perform the initial iteration of system definition and composition, up to, but not including, preliminary design.

Second, this thesis performed a preliminary analysis to demonstrate the potential benefit of developing an ISHMS for aging aircraft, using the A-37 aircraft as an example. Basically, the calculations presented in this thesis are meant to provide rough estimates that could be used to support a financial decision for funding the development of an ISHMS, based on several assumptions that will be explained in future

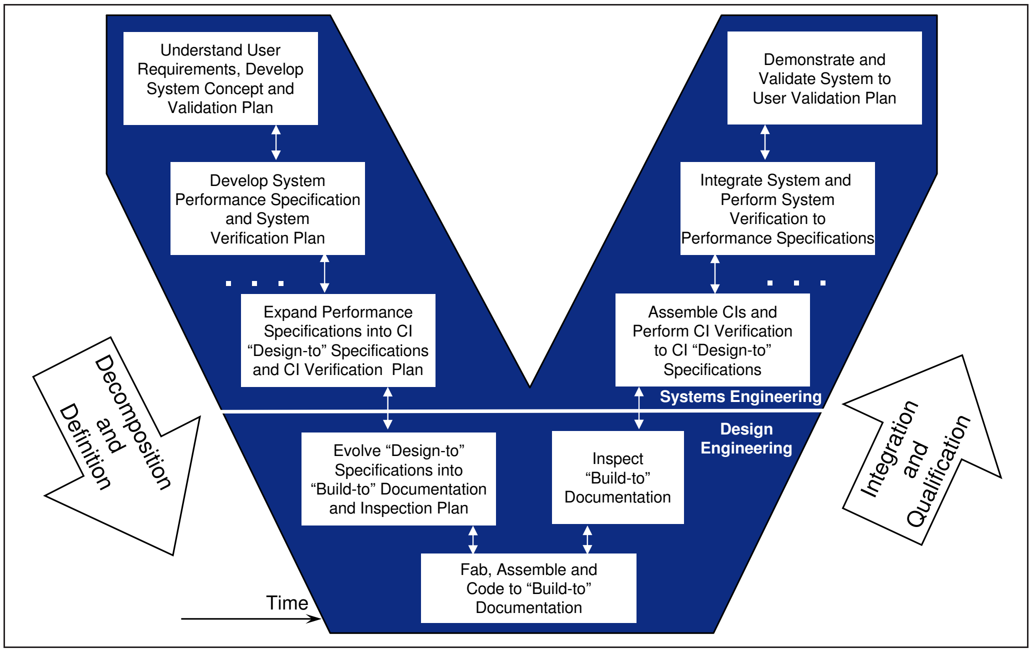

Figure 1.3: Vee Model [17]

chapters. Using material analysis and crack growth modeling, simplified simulations were created to compare the benefits of utilizing an ISHMS on aging aircraft to the status quo of flying without an ISHMS installed. The potential benefit of an ISHMS was determined from both the safety and cost perspectives. Cost savings achieved from reduced maintenance inspections constrain the maximum limit of the ISHMS development, procurement, and installation costs. From a purely cost standpoint the ISHMS would not be beneficial if its life-cycle costs exceeded the cost savings it provided. Any additional positive and negative effects beyond the maintenance realm were also considered. For example, if an ISHMS limited the aircraft performance significantly enough to degrade aircraft mission effectiveness, then the ISHMS would not be beneficial, even if the maintenance costs savings were favorable.

This thesis is organized in an attempt to walk you through the various steps from identifying the problem to recommending further research areas to solve the problem. The next chapter, Chapter 2, provides a more detailed description of the background associated with the problem and summarizes the findings of the relevant literature pertaining to the problem and its background. The team decided to concentrate on

the development of an SE approach to an ISHMS. Chapter 3 explains the scope, or boundaries, of the problem and the methodology used to solve it. The results of implementing the methodology are presented in Chapter 4. Finally, Chapter 5 declares the conclusions drawn from this study and provides recommendations for further research in this problem area.

II. Aging Aircraft and Structural Health Background

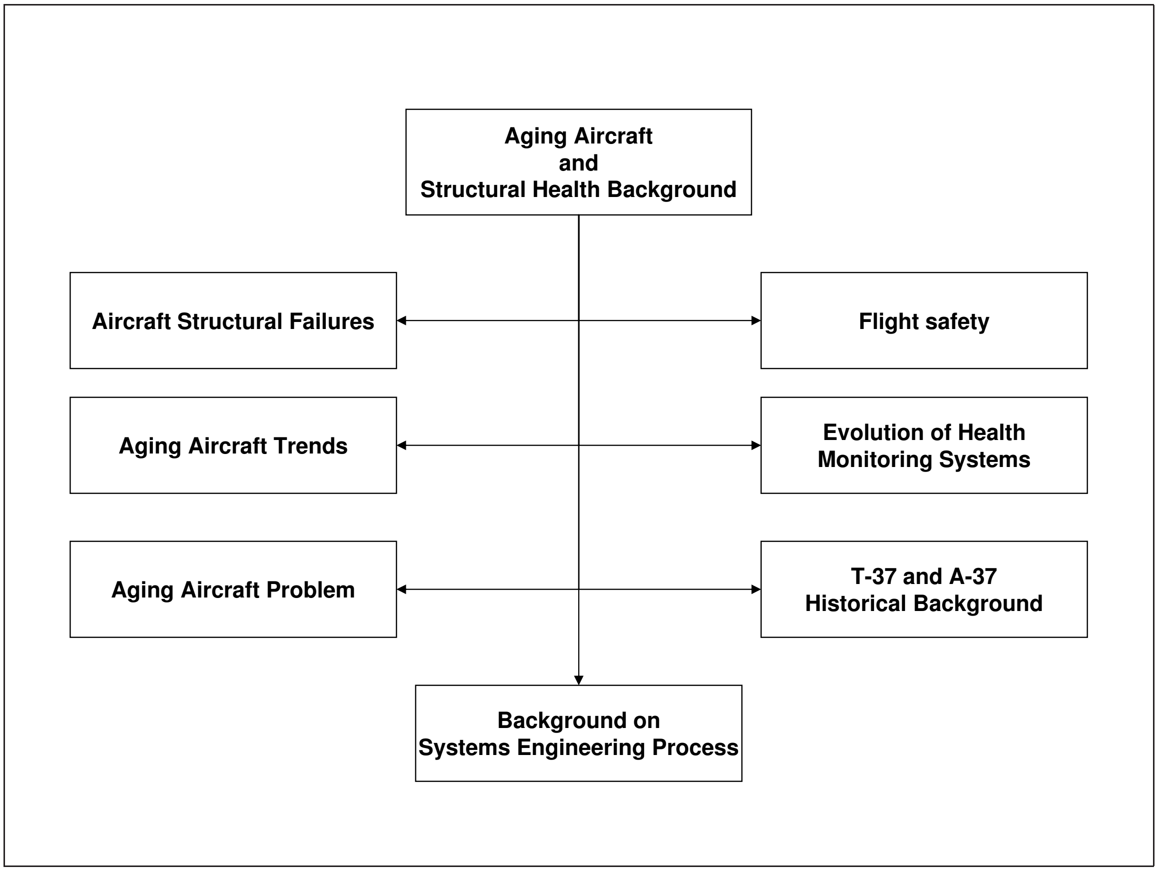

Figure 2.1: Chapter 2 Decomposition

This chapter (Figure 2.1) provides the background on the problem of aging aircraft and structural health. The chapter begins with a look at aircraft structural failures and how flight safety is determined, specifically with respect to aircraft structural failure. Next, it contains a review of aging aircraft and the associated issues and problems. This leads to a summary of structural health monitoring implementations to-date and an examination of solutions to maintaining the safety of aging fleets with limited budgets. The chapter then provides a more detailed review of the issues associated with the aging A-37 and T-37 aircraft. Finally, a summary of the systems engineering process is presented.

2.1 Aircraft Structural Failures

Structural failure occurs when a structure breaks in such a way that it can no longer carry as much load as it could before the failure [2]. A failure of any aircraft structure can be catastrophic. Aircraft structural failures usually result from design and manufacture flaws, maintenance damage, or damage occurring during operational use. Structural damage resulting from maintenance actions is rare. In fact, operational use exacerbating an existing flaw from design or manufacture is most often the reason for aircraft structural failure. A complete understanding of aircraft structural failure phenomenon enables engineers, maintainers, and other key personnel to correct or mitigate problems before structural failure occurs.

While rare, maintenance personnel can cause damage to aircraft structures in innumerable ways. Maintainers may perform improper maintenance, using the incorrect maintenance practices, and wrong materials, parts, or tools. These foreign parts or materials may not perform as required and can cause damage to neighboring structural elements that may see increased loads as a result. When reassembling the aircraft, maintainers cannot assemble the aircraft back to its precise configuration prior to disassembly. This change in aircraft structural configuration can change load paths on structural elements. The mere act of walking, leaning, or sitting on structural members may impart a load on a structural element not seen during operational use. Maintenance is critical to the aircraft, and aircraft maintainers are skilled, talented individuals. As stated, rarely will maintainers cause any significant structural damage to an aircraft; however, the possibility exists and must be considered.

The type of damage that causes structural failure usually is born during the design or manufacturing stage. Similar to maintainers, the aircraft manufacturing technician may unknowingly introduce damage to an aircraft. Again while rare, technicians may not assemble exactly to the design and introduce unintended loads. Aircraft designers can also introduce flaws through poor design and poor selection of materials. Even if a person could discount maintenance, all materials have internal

flaws due to design and manufacturing induced flaws, that are not perceptible during manufacture and contribute to variability in material strength. It can be generally assumed that these material flaws exist in all new aircraft, and these flaws will eventually become cracks. These imperceptible flaws will most likely be the eventual root cause of structural failure when exposed to the punishment of aircraft operations.

Operational use is the main cause of structural damage. Occasionally, in-flight damage such as bird strikes can contribute to structural damage. However, the main causes of structural damage and, ultimately, failure are the repeated loading and cycling that occurs on the structure from takeoffs, landings, flight maneuvers and aircraft weapons and g-loads. The severity and frequency of the loading and cycling directly correlate with how quickly and to what degree structural damage occurs. Today, the operational use of many aircraft exceeds that for which it was originally designed. This translates to quicker and more rampant structural damage than was estimated during design.

The most probable locations for structural damage resulting from operational use are known as fatigue critical locations (FCL). FCLs are where local stresses are usually highest. Fatigue critical locations can also result from a particular structural element's material or design that makes it more susceptible to fatigue. Examples of common FCLs are joints, rivet holes, and bolt holes.

Corrosion and fatigue represent the two highest concerns regarding structural damage. Corrosion only occurs during operational use. Fatigue, as mentioned, is an exacerbation, during operational use, of a previous condition. While corrosion is theoretically preventable, fatigue is not. Fatigue will eventually lead to structural failure. When failure occurs depends on the number of inherent flaws, the location of the flaws in the aircraft, and the severity of operational use.

Typically, corrosion alone is not a cause for structural failure. Corrosion is inspected for during maintenance and removed or structures are replaced wherever found. Detection inside the aircraft is usually limited to visual means; therefore,

corrosion may not be discovered on some structural elements. This undiscovered corrosion can cause a significantly decreased damage tolerance in a structural element. For instance, if a crack were to propagate in a corroded structural element, the combination of the crack and corrosion would decrease the elements strength greater than either one alone.

Structural fatigue resulting from repetitive operational use is the primary cause of structural failure. For example, aluminum, a type of material used in aircraft design, does not have an endurance limit; therefore, it accumulates damage with use. Use generates fatigue, so to avoid fatigue would mean to avoid use. This is not practical, thus fatigue is not preventable. Fatigue must be understood and monitored to mitigate the potential catastrophic effects.

Fatigue generally results from two types of loading: low cycle and high cycle. Flight maneuvering and aircraft loading generate low-cycle fatigue. Low-cycle fatigue usually has a higher amplitude and lower frequency than high-cycle fatigue. Vibration from aerodynamic, mechanical, or acoustic sources leads to high-cycle fatigue. The loads generated from flight maneuvering and aircraft loading can be estimated quite well during aircraft design. These estimations remain quite accurate as long as the aircraft operates within the original design parameters for operational use. In contrast, the high-cycle loads can also be estimated during aircraft design, but these loads will most probably change later in the aircraft's life. This phenomenon occurs due to changes in the response of the structure due to wear, repairs, structural cracks or variations in operational use or aircraft configuration.

Cracking is a result of fatigue. Since cracking can not be prevented, it needs to be precisely predicted such that aircraft safety can be maintained. Crack prediction encompasses timing of crack initiation and crack growth speed. Progress has been made in the areas of crack initiation and small-crack growth, but predictive modeling of these phenomenons still eludes the scientific community [61]. If initiation and growth are accurately predicted, timing of critical crack length can be predicted.

Critical length is defined as the crack length that will cause structural failure of the fatigued element. This assumes a single crack in an element. Widespread fatigue damage (WFD) complicates the problem further. The existence of multiple cracks of sufficient size and density to decrease strength is WFD. The multiple cracks may occur in the same structural element or adjacent structural elements. Whenever and however cracking occurs, the more accurately it can be predicted and the effects on structural strength analyzed; the longer aircraft can be safely flown prior to maintenance action or aircraft retirement. [61]

Cracking is such a critical safety issue that aircraft designers account for its occurrence during design. Typically, aircraft designers account for structural cracks through two design approaches, safe crack growth design and fail-safe design. Safe crack growth is typically used for high-performance combat aircraft where weight is a considerable consideration. Safe crack growth design ensures that the maximum probable undetectable initial manufacturing flaw will not grow to critical size in any critical structure during the operational life of the aircraft. This requires a considerable engineering analysis using crack growth prediction models. Since the prediction models are not precise, a large safety factor is introduced. Additionally, concerns exist with not accounting for all possible FCLs in the original analysis. Other locations may also become critical in aging aircraft. Fail-safe design relies on multiple, redundant load paths or crack arrest features to mitigate the effects of cracks. This design approach is typically used in larger aircraft.

Understanding aircraft structural failures and their causes is a complex problem. While work is still being done, predictive models are not always accurate. Detection of structural damage can be difficult. Overall, structural integrity issues for aging aircraft are particularly difficult because the damage under consideration consists of multiple interacting flaws and the crack sizes are often in a range where the phenomenon is complex and not well behaved [61].

2.2 Flight Safety

Aircraft in-flight safety is critical. Obviously, a critical failure occurring during flight affects flight itself, and thus could spell catastrophic consequences for the aircraft, its crew, passengers, and cargo. As such, a balance is struck between the accepted risk of critical failure and aircraft life. The accepted risk and aircraft life calculations have varied over time and still vary among different aircraft users, manufacturers, and stakeholders today. Often, the estimated aircraft life is based on a very low level of probability of failure along with a high safety factor to account for variability.

The aircraft's life is calculated at several different intervals of time. When an aircraft is first designed, a preliminary calculation sets the design life. This design life is based on the expected flight profiles the aircraft will operate within, such as, maximum g-loading, maximum flight speed, average flight speed, number of takeoffs and landings, average flight altitude, static loads within the aircraft body such as passengers and cargo, or any loads carried on the wings. The calculations translate the flight loads down to local stresses on structural elements. Based on the expected stresses over time, estimations are made on how long, often expressed in flight hours, the highest stressed elements will last before critical failure. Typically, the safe life is calculated as the design life. The safe life is defined as the estimated mean fatigue life of the aircraft structure divided by a scatter factor [65]. The scatter factor ensures the probability of failure is low. To maintain a high degree of confidence in this life estimation, inspections are often performed on the structural elements that form the basis for the design life, or the FCLs. If the inspections find damage occurring before the expected timeframe, those structural elements may be replaced or redesigned. This modification along with general aircraft maintenance will affect the original design life, often extending the life. Additionally, inspections can be accomplished to verify that the original design estimations regarding damage were accurate. This can be quite challenging. Even when actual historical damage data is gathered, further crack growth and critical crack length must be estimated.

In general, the safe-life estimation led to aircraft being retired long before their time. For example, if the accepted cumulative probability of failure was 99.9% over the life of the aircraft, then for a fleet of one thousand aircraft, 999 were being retired still having some useful life. This dilemma led to the fail-safe philosophy where a planned inspection process was spelled out. Aircraft were allowed to continue flying until damage discovered from planned inspections was enough to retire the aircraft. This philosophy spawned the Aircraft Structural Integrity Program (ASIP). The ASIP detailed the required inspections for varying aircraft. The ASIP also worked to determine residual strength of structural elements given crack growth. It was during this time non-destructive inspection (NDI) techniques became even more important. Since the fail-safe philosophy was attempting to push the envelope on aircraft life, the inspections, this philosophy required, needed to be able to detect as much of the relevant structural damage as possible. [65]

Eventually, the fail-safe philosophy was abandoned under the ASIP and the damage tolerance philosophy was adopted. The damage tolerance philosophy works much like the fail-safe; however, it puts more of a focus on understanding operational stresses and loads and how they affect crack growth and structural fatigue. This was beneficial because many aircraft users were exceeding the original operating parameters and the older methods did not consider this change would not be as accurate. Damage tolerance assessments considered the different cycling loads, different aircraft designs, and high-cycle and low-cycle fatigue. As such, different classes of aircraft required different damage tolerance methodologies. Overall, the damage tolerance approach calculates crack growth deterministically using constant material properties and a known initial flaw size. This deterministic approach to the stochastic problem of structural damage has led to new approaches being developed and analyzed today. [65]

The probabilistic approach had been born to address the stochastic nature of crack development and growth and variability in material properties. Additionally,

the probabilistic approach may be able to safely extract more life from an aircraft in today's times of reduced budgets.

Today, the life of an aircraft fleet is no longer governed by its original design life. To a great extent, the life is determined by the mission need, the maintenance cost, and the economic considerations required for the fleet to continue its operational requirements [65].

2.3 Aging Aircraft Trends

Structural health concerns are focused on aircraft with increasing age. Civilian and military aircraft inventories have both experienced a gradual and continual increase in the average aircraft age. In the *civilian* general aviation market, the high cost of new aircraft reduced new aircraft purchases resulting in legacy aircraft usage beyond the original design service life (Figure 2.2).

Civilian commercial and general aviation aircraft inventories have both increased in average aircraft age. The high cost of new aircraft forced the civilian *general* aviation market to purchase and maintain legacy aircraft beyond the original design service life (Figure 2.3).

Similarly, the high cost of Operations and Maintenance (O&M) of legacy *military* aircraft combined with the high cost of new aircraft purchase created an aging military aircraft fleet. This trend showed that the United States was unable to purchase enough new aircraft each year to reduce average aircraft age. This inability to reduce the average age of the United States military aircraft has been coined a "death spiral" by the Joint Council on Aging Aircraft (JCAA). The "death spiral" started with deferring modernization and recapitalization due to constrained resources. This resulted in the further increasing the age of weapon systems with an associated increase in maintenance. This increased maintenance drove up O&M costs and reduced readiness, which then required the shifting of funds from procurement accounts to O&M to keep our existing systems mission capable. The Congressional Budget Office

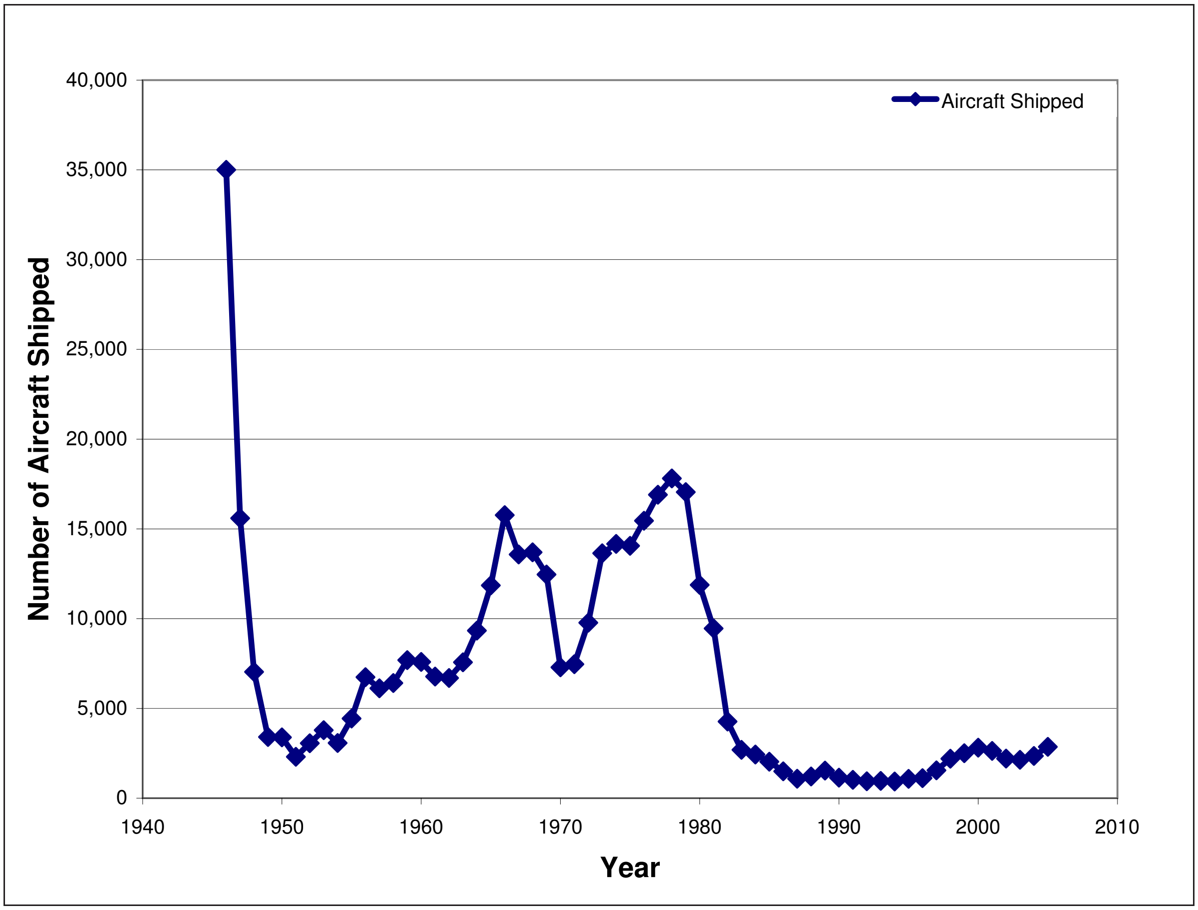

Figure 2.2: General Aviation Aircraft Manufactured [33]

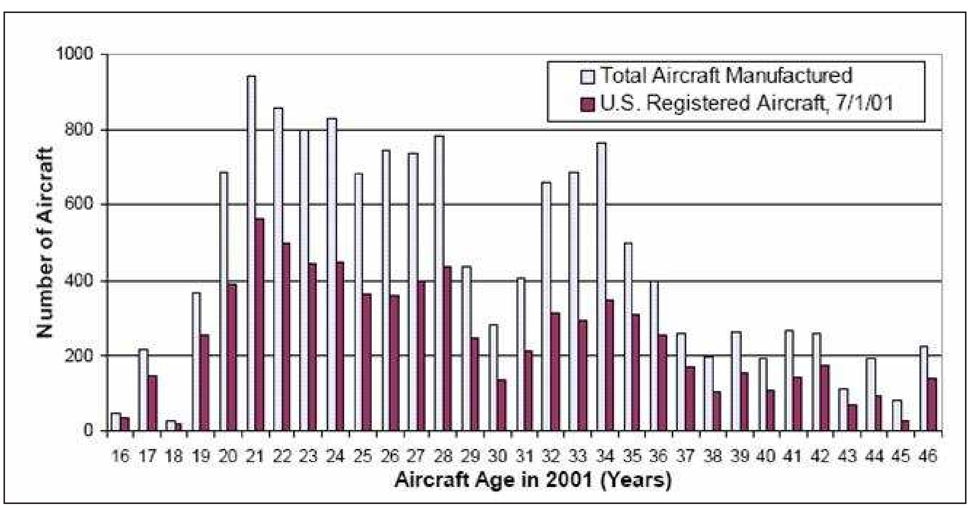

Figure 2.3: Number of Aircraft vs. Age [22]

(CBO) estimated "spending on O&M for aircraft increases by 1 percent to 3 percent for every additional year of age, after adjusting for inflation" [43]. These market forces created an increase in the average age of military aircraft (Figure 2.4).

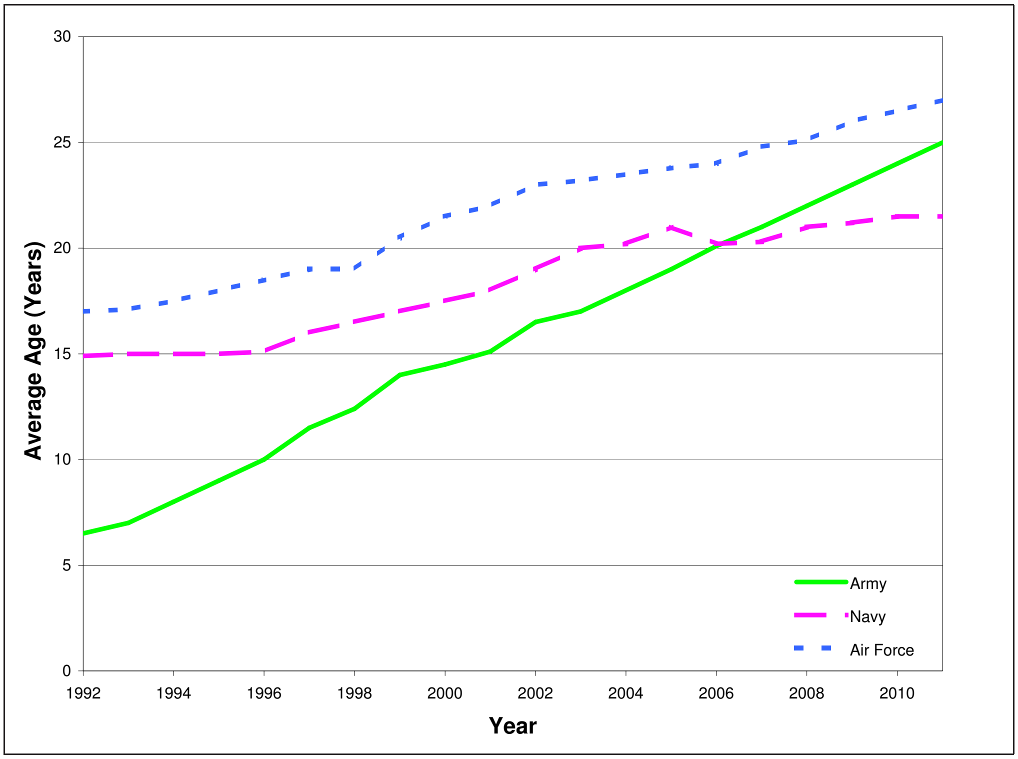

Figure 2.4: Average Fleet Age [42]

One of the reasons average aircraft ages were increasing was the high cost of purchasing new aircraft. The civilian general aviation industry incurred a large cost risk from future aircraft liability litigation as well as regulatory cost of compliance. The high cost of future legal defense, settlements, and regulatory compliance negatively impacted the ability to produce general aviation aircraft at a low cost. The Manufacturers Alliance (MAPI) estimated 90% of aircraft fatalities resulted in a lawsuit of the aircraft manufacturer, even though historically 85% of crashes were the result of pilot error [52]. The rising cost of litigation parallelled the increase in lawyer supply as well as a reduction in the burden of proof in aircraft liability cases. The increasing numbers of lawyers (Figure 2.5) versus the number of United States citizens coincides with the California Supreme Court initiated change in product liability

laws in the 1960's to the 1970's. The product liability laws changed to the precept of *strict liability* decreasing the burden of proof from having to show negligence to only having to show a product defective. In 1978, "manufacturers of private aircraft faced liability insurance expenses amounting to an average of $100,000 per aircraft produced" [53]. This concept of *strict liability* spread throughout the United States court system in the 1970's to the 1980's and, coupled with the increasing lawyer capacity, was widely blamed for the rise in the cost of general aviation aircraft and the demise of the general aviation industry.

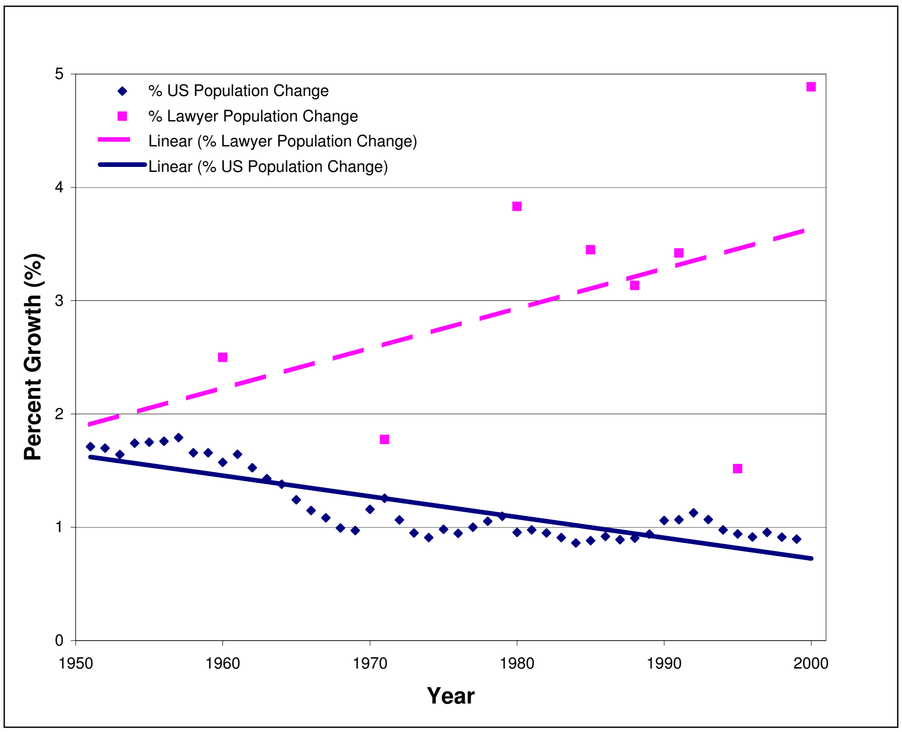

Figure 2.5: US Population vs Lawyer Population Growth [8]

The legal costs of the aviation industry worsened with increasing aircraft age. Aircraft operating beyond original service life created a series of accidents and incidents spurring Congress to mandate new regulations. The increase in regulations increased the cost of regulatory compliance. New regulations enacted by Congress occurred in waves after high profile aircraft accidents/incidents. One example of a high visibility structural failure was that of the 1988 Aloha in-flight decompression.

The fatigue failure of an Aloha Airlines Boeing 737 on April 28, 1988 (Figure 2.6) resulted in Congress passing the Aviation Safety Research Act of 1988.

Figure 2.6: Boeing 737-200 Catastrophic Failure [37]

The Federal Aviation Administration (FAA) responded to the Aviation Safety Research Act and concerns related to the increasing age of aircraft fleets by developing the National Aging Aircraft Research Program (NAARP). The purpose of NAARP was to ensure the structural integrity of high-time, high-cycle aircraft. The NAARP cornerstone was the development of commuter aircraft supplemental structural inspections. The supplemental structural inspections were required by Supplemental Inspection Documents (SID). These inspections were required for large aging transport aircraft starting in the 1980's and have successfully ensured the structural integrity of these aircraft. From 1980-1990, initiatives were created to extend this SID process to conduct damage tolerance assessments on the airframes of small aging commuter aircraft. While the Aviation Safety Research Act of 1988 was successful, each new wave of legislation increased the regulatory burden placed upon the aviation industry. Increasing the regulatory burden increases the cost of compliance, and results in a higher cost of new aircraft. The regulations impacting the cost of new aircraft in-

clude: The 1946 Federal Tort Claims Act which allows cases to be brought against the federal government for the negligence of air traffic controllers, but limits liability of military members (or survivors) to bring suit against the government. The 1958 Federal Aviation Act and Regulations which established the FAA and set minimum safety standards for flight operations and aircraft manufacture. The 1976 Foreign Sovereign Immunities Act defined foreign states and limits suits against foreign governments and foreign aircraft industries. Most importantly states dictate applicable law (i.e., product liability rules). Additionally, the cost of litigation is heavily influenced by state and federal laws; personal injury and wrongful death damage standards, "tort reform" (limitations on recovery) measures, military contractor defense (limits manufacturer liability), and workers' compensation (limits the employer liability). The regulatory cost of compliance in the aviation industry is ever increasing. The 1996 Aviation Disaster Family Assistance Act required that airlines must offer crisis counseling, make hotel rooms and food available, help family members retrieve dental records and X-rays to identify the victims, provide transportation to and from the crash site, and airlines should even consult family members about a memorial. Increased litigation and regulation created an increased financial risk for general aviation industries. This increased risk created an increased cost to mitigate the risk and resulted in an ever increasing cost of aircraft (Figure 2.7). The increasing cost of general aviation aircraft reduced the market demand and resulted in many general aviation aircraft builders going out of business. [33]

In 1994, Congress moved to mitigate the external impact of increased litigation on the general aviation industry. The United States Congress passed the General Aviation Revitalization Act (GARA), which limited the liability of an aircraft manufacturer to 18 years after aircraft delivery. While this change in the legal system saved the last few aircraft manufacturers, the number of general aviation aircraft manufacturers and aircraft manufactured had dwindled (Figure 2.8). The contraction in the number of general aviation aircraft manufacturers reduced the free market ability to keep aircraft prices down through open competition.

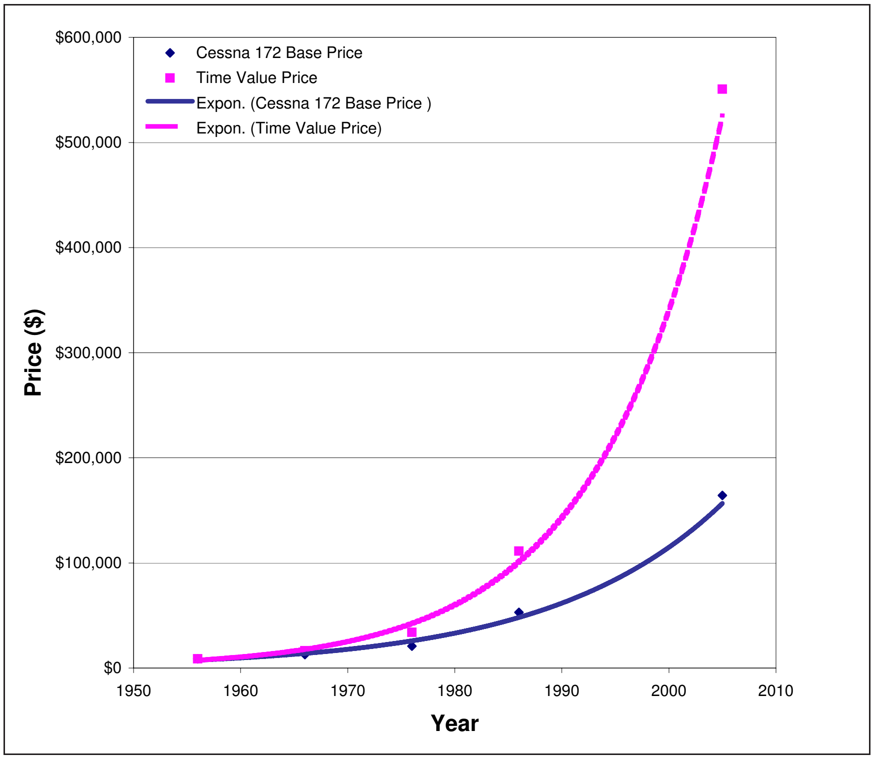

Figure 2.7: Cessna 172 Price vs Time [22]

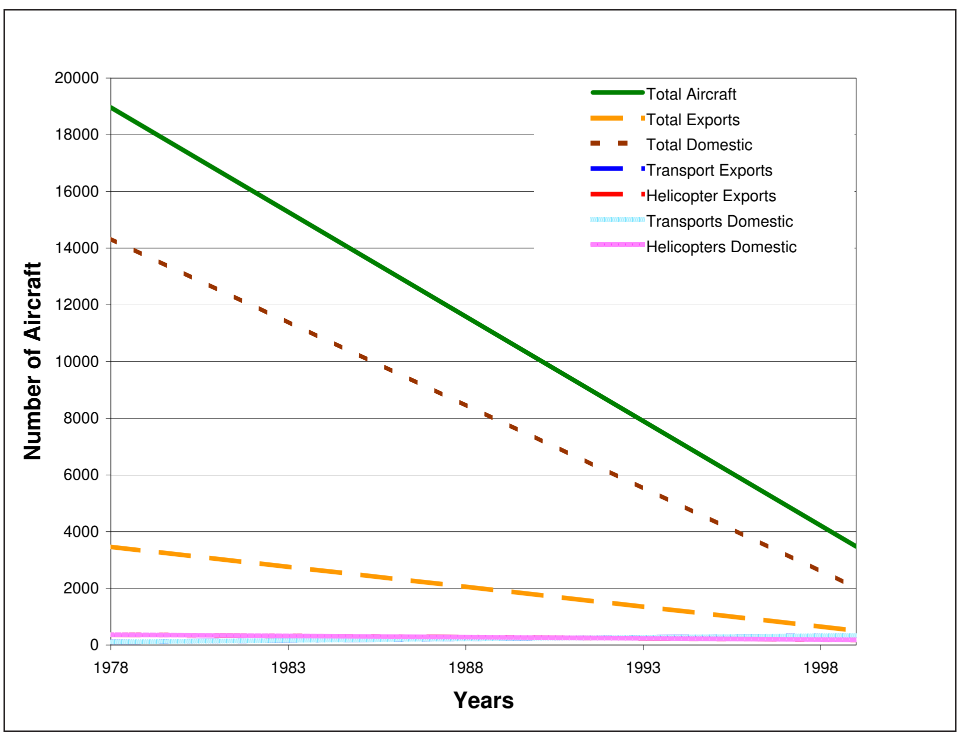

Figure 2.8: United States Aircraft Production [21]

A series of external liability and regulatory factors increased the cost of manufacturing an aircraft. This increase in new aircraft cost led many countries to conduct a series of structural life extension programs to maximize service life of aircraft in their inventory. The systematic process of extending aircraft service life coupled with low numbers of new aircraft purchased created an overall increase in the average aircraft age of both military and civilian aircraft.

The result of the increasing age of civilian and military aircraft can be broadly categorized into increased downtime for large inspections and increased cost of inspections and repairs. Additionally, there is a hard-to-quantify effect on aircraft safety as fatigue and environmental factors effects become wide-spread issues. Currently, the National Transportation and Safety Board (NTSB) show only a small percentage ($\sim$10%) of aircraft accidents are caused by structural failures (Figure 2.9).

The potential for increased failures is caused by the aircraft age magnifying the effects caused by: additive damage of improper usage, the compounding effects of limited/improper maintenance, limitations in design beyond the original service life, unforeseen material selection interactions (stress corrosion cracking), material imperfections becoming stress concentrations for fatigue critical locations, replacement parts substandard micro structures/crystal structure/grain size/microvoids caused by material impurity or heat treatment/processing deficiency. Additionally, early fabrication errors may be lurking time-bombs with assembly error, machining error (stress concentrations), welding heat treatment effects interacting with fatigue conditions, creep, and combined loading.

2.4 Evolution of Health Monitoring Systems

In recent years, there has been an increasing effort in the aerospace domain for the development of structural health monitoring systems for aircraft and aircraft components. Aerospace manufacturers and numerous institutions around the world have been working in this area and their research has been moving in many directions.

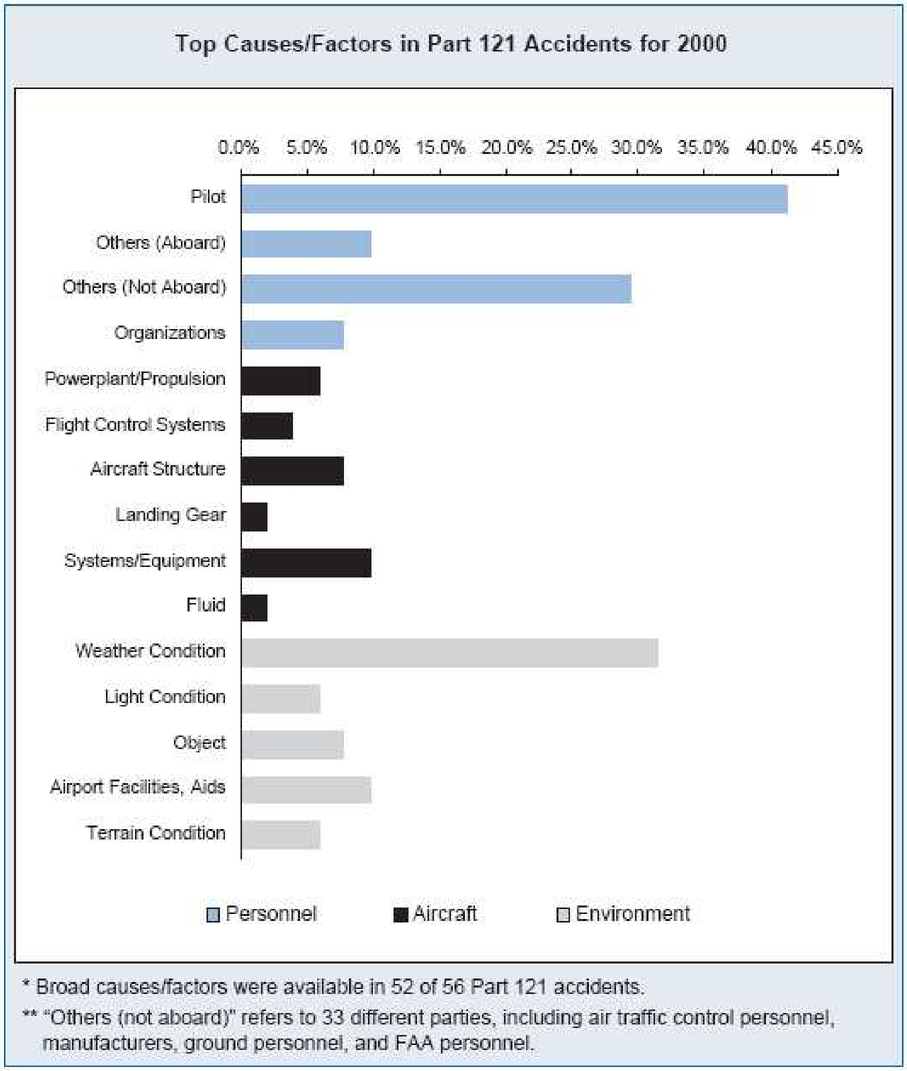

Figure 2.9: Aircraft Failure Causes [51]

The *traditional* approach of aircraft maintenance is to conduct inspections periodically based on a schedule. During the system's design a number of critical locations are identified and a maintenance schedule is developed with the purpose of inspecting these locations. As the system goes into service, the periodic inspection schedule is reevaluated and new areas requiring inspection may be identified, or the inspection frequency for some other areas may be modified.

The periodic scheduled inspections are performed for some critical areas and selected components of the aircraft, while other areas and difficult to reach components are being inspected less frequently or whenever access to them is gained due to other maintenance actions.

Approximately 90% of these conventional inspections [13] are visual inspections and most of the remaining percentage are NDI. The visual inspections consist of intensive checks using inspection aids (such as mirrors, lenses, etc) and require the involvement of the maintenance technicians. During these inspections, the technicians are trying to identify structural irregularities before they become critical and their results sometimes depend on the technician's ability to access the inspected area and to correctly assess its condition.

The NDI and Non-Destructive Evaluation (NDE) techniques consist of some of the following:

- ultrasound inspections, eddy currents
- Magnetic Particle Inspections
- Fluorescent Penetrate Inspections
- x-ray inspections

These techniques provide some level of *automation* of the inspection procedure comparing to the visual inspections. A basic limitation of these methods is that these techniques can only inspect and detect specific types of flaws. Ultrasounds, for example, are efficient in detecting corrosion and flaws in composites and surfaces;

Eddy currents are efficient for fatigue cracking detection. Also, these methods are generally customized to inspect a specified area (e.g. different ultrasound probes are developed to inspect different areas). Some NDE inspections may be performed once while some others may require extensive preparation and/or significant system downtime. Although these inspections can be more effective than conventional visual inspections, they only provide a *snapshot* of the inspected area at the time of the inspection.

According to the *traditional* approach, aircraft maintenance is based on recording and monitoring parameters such as flight hours, mission type and duration, aircraft configuration flown, etc. These parameters are used to schedule the maintenance for each individual aircraft and also to manage the total fleet. A basic assumption is that fleet average parameters match those of the individual aircraft.

As the experience and knowledge on aircraft use and maintenance practices increased worldwide, it became understood that each aircraft operator has a different system usage. There is different usage of each individual aircraft in the same fleet and that the approach of conducting maintenance based on fleet wide average parameters is not accurate enough. Especially, the operators of military aircraft (fighter, trainer, attack aircraft) realized that there is substantial variability in their usage profiles and that their aircraft cannot be tracked based only administrative parameters such as flight hours. Also, the operators realized that the actual usage loading on their systems was more severe than that predicted from the design models. More accurate methods for aircraft systems management were developed but there is still a large variability among the different operators. As a result of this understanding, the concept of a fatigue management program and the idea of a *Structural Health Monitoring System* (SHMS) have emerged.

2.4.1 Fatigue Management Programs. *Fatigue management program* follows an integrated plan comprising of 4 factors [7]. These 4 factors are the fatigue management process, an individual aircraft tracking program, a fatigue monitoring system,

and the calibration of fleet results. The fatigue management process starts during the design of the system and continues during the system's operational life with fatigue monitoring, which is the process of collecting operational loading data. The reason for performing fatigue monitoring is to record the actual operational loading history of the aircraft, to ensure that the aircraft is not operated beyond an acceptable risk level, and to ensure that the aircraft will *survive* at least throughout its design life under normal operating conditions. As part of the fatigue management program, the collected loading data is used in order to improve the systems structural integrity.

The first fatigue management programs were mainly centered around load monitoring. The reason is that operational loads are an essential parameter for describing the aircraft usage and predicting the system's residual life. The loads were monitored by using strain gauges installed at various points on the aircraft or by recording flight parameters and calculating (using mathematical models) the resulting loads for the critical locations. The main advantages of this approach are that it allows the actual usage to be determined, it helps the user operate the aircraft accordingly, and it allows the residual life of the system to be fairly accurately estimated. This approach for conducting fatigue management guarantees the safe-life performance of the aircraft and is very popular among the operators of military aircraft.

The more current approach for managing the fatigue on an aircraft is by damage monitoring. Fatigue management programs based on this approach are still in the development stage. This type of program tries to record and monitor the initiation and development of cracks at various points on the aircraft. The goal is to be able to detect the degradation of the aircraft structure and to avoid critical failures. Monitoring the crack length (measure of the damage), the crack growth (which defines the rate of damage accumulation), and the prediction of the fracture point of a component should be made with an accuracy that will allow the aircraft to be operated within the acceptable risk levels. The basic idea behind damage monitoring is depicted in Figure 2.10.

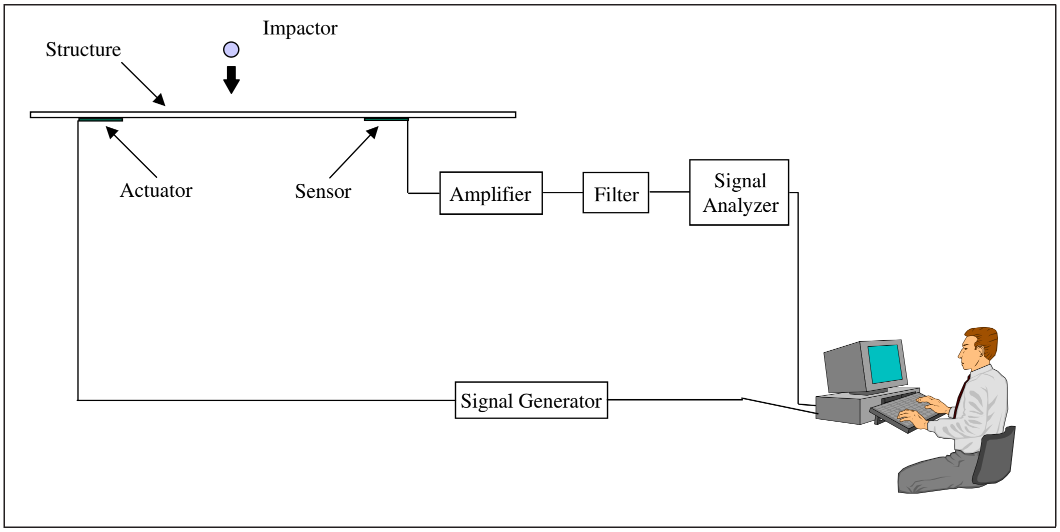

Figure 2.10: Principle of Damage Monitoring [13]

The corrosion prevention plans are also part of the fatigue management programs. The prevention of corrosion is a major issue for aircraft manufacturers and operators. The reason is that it is difficult to detect the initiation point of corrosion. Also, the effects of corrosion on the system increase nonlinearly as the age increases.

The individual aircraft tracking program (IAT), used as part of the fatigue management program, allows the development of a maintenance schedule, including inspections, repairs, and modifications for each individual aircraft. It also allows the maintenance to be scheduled and performed not based on flight hours but on the actual fatigue loads and/or crack lengths of the aircraft. Such a program is very beneficial especially when there is great variability in the operational use of the aircraft among different users (e.g. different squadrons). It allows the identification of usage trends, the controlled life consumption of the system, and the modification of the operational usage (if necessary). Moreover, the operators do not need to rely on fleet-wide average parameters since each aircraft is being monitored individually.

2.4.2 Health Monitoring Systems. The basic idea behind the health monitoring systems is a system that is installed on an aircraft and continuously monitors parameters such as strain, vibrations, electrical signals, acoustic waves, temperatures,

etc exercised on the components/systems during their operation. The health monitoring system would allow the operators to obtain frequent views of the systems condition instead of getting snapshots whenever an inspection is performed. These *frequent views of the system* would allow the operators to diagnose the condition of the aircraft at any moment during its life and make predictions about its future state. A system performing this monitoring could consist of a set of sensors installed on the components or the aircraft structure. Figure 2.11 represents a depiction of this concept.

A health monitoring system is the most *advanced NDE method*. It allows nondestructive inspections to be performed continuously on numerous points of the system, even the most inaccessible areas, and (comparing with the conventional NDI) provides frequent views of the system's condition. This way the NDE technology becomes an integral part of the aircraft structure.

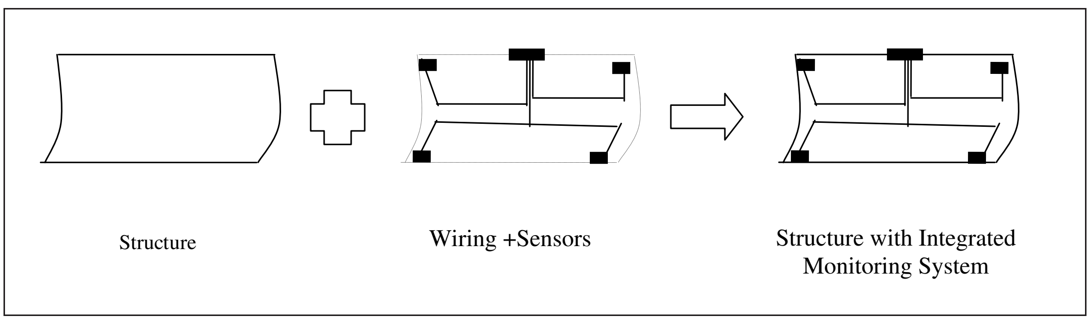

Figure 2.11: Monitoring Integration on a Structure [7]

The first applications of monitoring systems were designed basically to monitor the operation of electronic components found in avionics and flight control systems. Other early monitoring systems were capable of performing loads monitoring of specific areas on the aircraft structure and the engine components. These systems collected loading and/or flight data from different points via sensors or through the existing parts of the aircraft. For example, pressure sensors that are part of the operation of an engine subsystem are being used also for collecting data for monitoring purposes. These systems had limited analysis capabilities. They recorded

the collected data which was later downloaded into a workstation for analysis and evaluation. The loads monitoring and flight data recordings were not continuous and were limited by the processing capabilities and storage capacity of the monitoring system's electronic parts. From the characteristics of the monitoring systems as described above, it is apparent that these early systems were not truly integrated with the aircraft.

In those early monitoring systems designs, the gauges had to be very close to the monitored area. The efficiency of these systems was largely dependent on whether an area was monitored and the occurrence of the damaging event was recorded. This means that, since only specific points were monitored, if a damaging event occurred at another point, it might not have been recorded.

As the sensors technology advanced, new smaller, less expensive, and more reliable sensing devices were developed. With the new technologies, it became feasible for the sensing and actuation devices to be integrated with the components and the structure. The most widely used types of sensing devices are piezoelectric and fiber optic sensors.

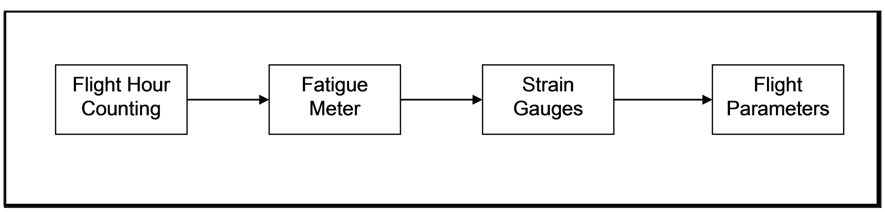

Figure 2.12: Evolution of Fatigue Monitoring Systems [7]

Piezoelectric sensors are mainly used to monitor accelerations and vibrations. New designs of ceramic piezoelectric sensors can be bonded on the structural surfaces and can even be integrated into composite materials (smart layer concept). The fiber optic sensors have the advantages of being lightweight, highly sensitive, and only require low-power consumption. These sensors can have a long lifetime and low costs but, on the other hand they are difficult to repair [13].

Together with the progress in the sensors design came a shift towards the concept of an ISHMS. The purpose of such a system is to continuously monitor the aircraft's *hot spots* and to be able to perform an analysis of the recorded data and generate maintenance *recommendations*. With an ISHMS, it is not necessary to monitor the entire aircraft; only the most critical locations need to be monitored. Networks of sensors monitoring these critical locations are designed and improved diagnostics algorithms are developed. The ultimate goal of these sophisticated ISHM systems is to function as the *nervous* system of the aircraft.

The use of the existing health monitoring systems has shown that these systems can help reduce the maintenance related costs during the life cycle of an aircraft and can improve the systems reliability. They can also help to migrate from the schedule based maintenance (the traditional approach) to conditional based maintenance on the aircraft.

Currently, the community is at a turn in the evolution of SHMS. Manufacturers and researchers from all over the world are working on the development of new types of sensors, such as thermal, or sensors that are using acoustic or electromagnetic waves, in order to improve the direct damage monitoring. They are, also trying to combine the sensors into networks and to integrate the monitoring systems into the new aircraft systems during the design phase. A higher degree of customization in the maintenance of each aircraft and fleets being used for longer time (service lives of 40-50 years will be more common) are expected as a result of the use of advanced ISHMS.

In general, one can discern a trend towards the *automation of the inspection process* and other maintenance actions. Besides NDI methods and the design of advanced monitoring systems, other efforts include the robot assisted inspections, where specially designed and equipped robots are used instead of technicians to perform the visual and NDI/NDE. The advantage of this concept is the use of these robots allows the performance of inspections in areas hard to reach with small effort and minimum

teardown. The data collected from the robots is transferred to a workstation where the data is further analyzed.

2.5 Aging Aircraft Problem

In the recent years, an increase in the number of aircraft flying throughout the world has been observed. A large number of these aircraft have become *aging* (e.g. aircraft that have been flying for more than 15 years) [13]. This percentage is continually increasing. There is also an increasing number of military aircraft that have been flown for more than 40 years (e.g. F-4, C-135, B-52). Additionally, many mature aircraft are reaching the end of their design life.

At the same time, many aircraft operators, both commercial airlines and governments operating military aircraft, have to deal with financial hardships as a result of budgetary restrictions. Since they have aging aircraft in their inventory, these operators have to decide whether to choose the (usually) more expensive alternative of purchasing new systems or continue using their existing aircraft. Very often, the operators' decision is to try to get as much benefit as possible out of their *investment* before they retire their aircraft. Operators are also seeking a more efficient use of their systems. This creates a worldwide demand for continued use of aging aircraft fleets.

This demand, though, is not easy to satisfy. As the aircraft age increases, the problems generated by fatigue and corrosion increase. Increased numbers of inspections and other maintenance actions (repairs, modifications) are required, which usually leads to decreased system availability. The maintenance related costs (which is the biggest cost driver) and the safety risks (mainly due to fatigue problems) are also increasing while the increased age creates restrictions in the operational use of the aircraft (e.g. configuration limitations, flight envelope restrictions). Therefore, for aircraft that are reaching their design life, a life extension is needed.

The aging problem became even more important after the Aloha airlines accident in the 1980's. That accident resulted in stricter airworthiness requirements and created pressure from the FAA towards the aircraft systems industry to deal with the aging aircraft problem. The stricter requirements translated into increased maintenance actions and costs.

This thesis mentioned that the problems generated by fatigue and corrosion are increasing with the system's age. Cyclic fatigue degrades the structural life capability, and its effects are even more substantial when combined with corrosion. This is not a big problem for the mechanical, or the high-cost electronic components, or even the engines, since these parts can be easily replaced. However, when it comes to the aircraft structure (which has a relatively low-cost), the effects of fatigue and corrosion combined with the age, becomes a very serious problem. The reason is because the structure cannot be easily modified, let alone replaced, after it has been designed and manufactured.

There have been many different approaches, or design philosophies, that tried to deal with the age generated fatigue and the life extension problems. Examples of such design philosophies are the *safe-life design*, *fail-safe design* and *damage tolerant design*. Several life extension concepts such as the SLEP and the ASIP have been implemented. Each of these approaches has been used in different aircraft types. Sometimes different approaches or combinations of approaches have been used for the same aircraft type. Historically, one could say that both approaches have been used equally on all the aircraft types that required a life extension.

2.5.1 Safe-Life Design. The main idea of the *Safe-Life design* concept is that the components and the structures are designed in such a way so that they can *survive* throughout their specified design life. This means that the components are expected to function without any maintenance requirements (fatigue inspections, repairs, modifications, etc), and are being replaced as soon as they reach a specified time. The replacement at the specified time is being done in order to maintain the

desired safety level. In order to determine the inspection intervals and the replacement time in the safe life approach, the designers are trying to forecast the crack initiation and growth.

The replacement of the components at a predetermined time, though, is a rather conservative approach. At the time of replacement, the components may not have fatigue cracks long enough to justify their condemnation. As a result, the condemned parts may still have some useful life remaining, which is wasted. If a crack has initiated and has grown on a component before it reaches its design life, then, as soon as the crack is discovered (during inspection), it has to be repaired resulting in aircraft downtime and maintenance costs. The safe-life design approach, also, does not take into consideration the corrosion, which, as it was mentioned earlier, combined with the fatigue can have serious impact on the component.

According to the fail-safe design philosophy, the components or structures are designed so that, if they ever fail, their failure will occur in such a way that it will cause the minimum damage to the system. This philosophy is trying to overcome the disadvantage of wasting useful life as experienced in the safe-life design.

2.5.2 Damage Tolerance Design. Another philosophy is the *Damage tolerance* design. This term is used to describe the design of a system that has the ability to withstand damage. *Safety-by-inspection* is the main idea behind this design. The objective of such a design is to ensure that cracks do not grow beyond a critical size (i.e. a size that could affect the system's safety level) during the component's design life. In order to design a component and a system using this philosophy, there are some issues that need to be answered:

- What types of loads will be exercised on the component during its operational life?
- What are the sizes of these loads?

- How long can the component endure operating under this loading before a failure occurs?
- Once a crack has initiated on the component, how long will it take until it reaches a critical size?

The other part of the aging aircraft problem, besides dealing with the age generated fatigue, is how to extend the aging aircraft's service life. Using the results of aircraft loading analysis, corrosion and fatigue testing, and damage tolerance analysis, the engineers can extend the aircraft's service life for a number of flight hours. The goal is to determine inspection intervals that will guarantee the required safety level. This extension is usually accompanied by some restrictions on the operational use (e.g., limitations in the flight envelope) and by more detailed and more extensive inspections.

2.5.3 SLEP. One solution that has been developed to achieve this service-life extension for various aircraft types is the SLEP. This solution involves the identification of the fatigue critical structural components on an aging aircraft and their subsequent replacement or modification before the service life can be extended. The purpose of these replacements and modifications is to ensure that the affected components will be able to operate throughout the extension period without the requirement for any additional maintenance (inspections, repairs, modifications, etc), an idea which is encountered in the safe-life design concept. The identification of those fatigue critical areas and the replacement or modification of the components is usually a time consuming process and requires a lot of effort to assess the effects of these maintenance actions to the safety level. The mid-life upgrade programs that are developed for the various aircraft types are also in the same direction as the SLEP.

2.5.4 ASIP. The other major concept that has been implemented in order to extend the service life of various aging aircraft is the ASIP. The basic idea of ASIP is to perform a major structural inspection after a number of flight hours or, even better, a number of fatigue cycles have accumulated, instead of replacing the critical components based on their accumulated operation time as in SLEP. The time this inspection will be performed differs for each individual aircraft. The areas where problems (fatigue cracks, corrosion) are identified can be either repaired or replaced. ASIP is more related to the damage tolerance design philosophy.

In order to develop and apply an ASIP, the identification of the structural critical locations is required. This is being done by using the results of the Major Airframe Fatigue Test (MAFT) conducted during design. Information obtained from periodic scheduled maintenance performed, after the aircraft goes into service, is being used to update the MAFT results. Based on this information, the areas where WFD in aging aircraft occurs, are identified. These areas require special attention during the structural inspection to ensure timely detection of fatigue damage.

Subsequently, a structural inspection program is developed with the purpose to inspect and, if necessary, repair the critical areas. Extensive teardown inspections are included in the structural inspection program as well as NDI (ultrasound and eddy-current inspections are essential actions in ASIP), component testing, and full-scale fatigue tests. Theoretical models are also being used to estimate and forecast the fatigue effects.

A result of the above analysis is a customized inspection schedule for each individual aircraft. Other results are major modifications and/or repairs aiming to improve the structural integrity of the aircraft. These modifications/repairs are also customized for each individual aircraft. This customization refers to both the extent of the inspections/repairs/modifications and the timeframe these maintenance actions are going to be performed.

In the early ASIP plans, that were developed for various aircraft, only the effects of fatigue were taken into consideration. The effects of corrosion on aging aircraft and actions to deal with those were not included. This approach has changed in the recent years and corrosion prevention and repair is now part of an ASIP plan.

After the installation of early SHMS on some aircraft types, obtaining and analyzing loading data for each aircraft became possible. This data was also used to assess the structural integrity of the aircraft and to develop the ASIP plan, simultaneously increasing the degree of customization in the maintenance of each individual aircraft.

The application of the concepts discussed above by many manufacturers and operators around the world allowed the safe service-life extension on many aircraft types and provided some solutions for the aging aircraft problem.

2.6 T-37 and A-37 Historical Background

The A-37 aircraft is part of a long evolution of the T-37 trainer aircraft, which was modified extensively to satisfy varying mission needs and engineering designs. In order to fully understand the history of the A-37 aircraft, it is necessary to start by explaining the development of its predecessor, the T-37 aircraft. During the early 1950's the USAF decided that a lower performance jet trainer was needed to bridge the gap between the propeller-driven trainers and Lockheed's advanced jet T-33 Shooting Star being used in the pilot training curriculum [62]. In the fall of 1952, eight manufacturers submitted a total of fifteen designs during the Request for Proposals phase. The Cessna Aircraft Company won the contract with their Model 318 proposal, designated the T-37 (nicknamed Tweet) by the USAF. The contract required a total of three prototype aircraft and the first XT-37 prototype made its initial flight on 12 October 1954. After extensive flight tests and several modifications, the USAF ordered 11 pre-production T-37A aircraft. The first was delivered and accepted in September, 1955. However, the T-37A did not enter USAF operational service until the summer of 1957, when it was used by Air Education and Training Command

to teach student pilots basic military maneuvers and techniques, excluding ordnance delivery and in-flight refuelling [62].

2.6.1 T-37 (Tweet) Development. The original T-37A aircraft had an empty weight of 3,870 pounds and a maximum gross weight of 6,400 pounds [62]. Each of the twin-engines generated only 920 pounds of thrust. The T-37A aircraft impressed USAF maintenance personnel for its ease of maintenance, easy access to all components, and low overall maintenance requirements [62]. A total of 534 A-models, including the 11 preproduction units, were manufactured by October, 1959. In early 1959, Cessna and the USAF agreed on a configuration update for the T-37 and on 6 November 1959, the first T-37B was introduced into the USAF fleet [62]. Among the most significant modifications were:

1. New 1,025 pound thrust Continental/Teledyne J69-T-25 engines.
2. A very high frequency omni-directional navigation receiver.
3. Military-standard Ultrahigh Frequency (UHF) radio transceiver.
4. A redesigned instrument panel layout.

In total, 552 T-37B aircraft were produced between 1959 and 1968, many of which were A-models retrofitted to the improved B-model standards. At the same time, Cessna and the USAF engaged in a military sales campaign to deliver T-37 aircraft to several countries under the Military Assistance Program (MAP) [62].

> The T-37's flight control system is basic and conventional: all primary flight controls (ailerons, elevators, and rudder) are operated via cables, pulleys, cranks, and push-pull rods while secondary flight controls (aileron trim tab, elevator trim tab, and rudder trim tab) are electrically operated from the cockpit. The fuel system consists of three fuel tanks; one on each wing and one in the fuselage. The aircraft's onboard fuel capacity was 2,000 pounds (309 gallons) of fuel with a maximum range of 470 nautical miles without external fuel tanks. [62]

As a trainer aircraft, the T-37 was considered a perfect introduction to military jet aviation because of its outstanding safety record, its side-by-side seat arrangement,

as well as for its maneuverability and stability throughout its flight envelope [62]. In addition, the T-37's acquisition and operating costs were the lowest on record.

2.6.2 A-37 (Dragonfly) Development. In 1961, Cessna used a T-37B as the prototype for a new fighter aircraft model designated T-37C [62]. The concept resulted from USAF interest in a small, cheap combat aircraft for counterinsurgency operations against fast, well-armed guerrilla forces. The aircraft was intended primarily for export to foreign air forces that could not afford the current front-line jet fighters. In order to allow carriage of the external stores, Cessna had to increase the structural strength of the wing spars. The new design included jettisonable 65-gallon wingtip fuel tanks and a single weapons station under each wing. For weapons delivery, the T-37C incorporated a K-14C computing gunsight and an AN-N-6 16mm gun camera. Each pylon could carry a rocket pod, a gun pod, a bomb of up to 250 pounds, or an AIM-9 Sidewinder air-to-air missile. However, the modified aircraft was 10% slower because it used the same engines even though its gross weight was increased by 2,000 pounds. The T-37 fighter concept provided limited ground attack capability, but according to Shiel, the aircraft was really suitable only as a ground attack training aircraft [62]. A total of 273 T-37C aircraft were built and all were sold to foreign countries under the MAP.

In 1963, the USAF Aeronautical Systems Division at Wright-Patterson Air Force Base (AFB) issued a contract to Cessna for the development and evaluation of two YAT-37D prototypes [62]. The most significant changes were:

1. Two General Electric J85-J-2/5 engines each generating 2,400 pound thrust.
2. A total of three weapon stations under each wing.
3. Armor plating (7/32-inch steel) on the cockpit floor and behind the seats for protection against ground fire from up to 30 caliber weapons.
4. Self-sealing fuel tanks able to sustain penetration by up to 30 caliber weapons.
5. Vortex generators located on top of the wings

6. GE GAU-2B/A 7.62mm Minigun mounted in the nose compartment with 1,500 rounds of ammunition.
7. Mk Mod 4 gun sight mounted in front of the pilot.
8. Wingtip mounted 95-gallon external fuel tanks.
9. Larger wheels and tires for use on unimproved runways.
10. Special avionics package for communication, navigation, and target acquisition.

After all flight tests and evaluations were performed, the prototypes did not lead to a production contract and on December, 1964 the prototypes were retired [62]. Nevertheless, the USAF again became interested in the YAT-37 as a replacement for the aging Douglas A-1E Skyraiders, which were performing well in the Vietnam War, but were sustaining heavy combat losses [32].

In August 1966, the two retired YAT-37 were refurbished and a fourth external weapons pylon was added under each wing [62]. The USAF issued a contract for the delivery of 39 AT-37D aircraft, which were redesignated A-37A, to be tested in combat in South Vietnam under Operation Combat Dragon. In the aircraft's first 3,000 combat sorties, no A-37A aircraft were lost to hostile fire [32]. The Combat Dragon Operation evaluated the aircraft on its performance on close air support, escort, and armed reconnaissance missions. The evaluation identified several areas for improvement, which led to the development of the A-37B Dragonfly (Cessna Model 318E) and a $3.6 million USAF contract for the delivery of 197 new A-37B aircraft. In addition, the contract required the airframe to be strengthened to a maximum gross weight of 14,000 pounds and to include in-flight refueling capabilities. However, many of the basic systems on the A-37 aircraft, such as hydraulics and electrical components, were the same as those found on the original T-37 aircraft [62].

Most A-37B aircraft Cessna produced were exported under the MAP, many of those going to South and Central American countries (Table 2.1) [62]. Additional A-37 aircraft were later provided to MAP countries as the aircraft were removed from active USAF service. Some of the exported aircraft had the refueling probe

Table 2.1: A-37 deliveries to the MAPA countries [62]

A-37 Deliveries to South and Central America			
Country	**Quantity**	**Year**	**Notes**
Chile	34	1974-75	
Colombia	26	1980	including 12 for anti-drug efforts
Ecuador	12	1975	
El Salvador	21	1983-84	including 3 replacements in 1991
Guatemala	13	1969, 1973	
Honduras	15	1974-75	
Peru	36	1974-75	including last production A-37B
Uruguay	12	1975	

removed or replaced with a shorter probe for use as a single-point ground refueling system. Since then, the A-37 aircraft has proved to be an ideal aircraft for operation by countries with limited defense budgets and smaller, less technologically advanced air forces [62].

Despite their success, many of the existing T-37 and A-37 aircraft are approaching or have exceeded the end of their design life. During the last two decades, the USAF has developed and implemented several programs designed to extend the life of these aircraft without jeopardizing the safety of flight. Two of these programs are the A-37 SLEP and the A-37 ASIP, both of which will be briefly discussed in the following sections.

According to the 2005 Air Force Almanac, there are still 283 T-37 aircraft in USAF inventory with an average age of 40.8 years [6]. There are only two older airframes in the USAF inventory, namely the B-52 with 42.8 and the C-135 with 42.6 years respectively. Even though these life extension programs have been quite successful in accomplishing their goals, the reality is that the T-37 and A-37 airframes are requiring an increasing amount of preventive maintenance and inspections. In most instances, this means extensive grounding time and escalating maintenance costs, which ultimately affects mission accomplishment. The USAF has decided to replace their aging T-37 fleet with Raytheon's T-6 Texan II aircraft. However, some MAP countries have limited budgets and can not afford the replacement of their aging A-

37 or T-37 fleet. These countries would prefer to see the development of an aircraft structural health monitoring system that would allow the continued operation of their aircraft without the increased maintenance burden.

2.6.3 Life Extension. Documentation on the service life of both the T-37 and the A-37 aircraft is quite limited mainly because these are outdated airframes. In addition, information on the A-37 aircraft is usually harder to find because it is no longer in the USAF's inventory, nor is it easily accessible because of foreign policies and clauses. Furthermore, there are many factors that can affect an aircraft's service life and those factors can vary drastically between countries, which further complicates the task of accurately and precisely estimating the additional service life of a fleet of aircraft. For example, environmental factors, aircraft loading factors, the aggressiveness of the flying profiles, operational usage tempo, maintenance schedules and procedures are only some factors that can have a tremendous impact on the service life of each individual aircraft. Nevertheless, the thesis group was able to contact the Ogden Air Logistics Center, Mature & Proven Aircraft Directorate (MAPA), Integrity and Analysis Engineering Branch (OO-ALC/LCEI) at Hill AFB who provided some information on the T-37 SLEP, the T-37 ASIP and the A-37 safe-life programs. The following is a compilation of the procedures and findings.

2.6.4 T-37 SLEP. Cessna Aircraft Company initially estimated the T-37's original design life to be 8,000 flight-hours and 20,000 landings [60]. According to the publication Cessna Warbirds, between June 1969 and December 1970, Cessna's Military Twin Division conducted an exhaustive fatigue life testing program on the T-37B with the goal of extending the Tweet's life to 15,000 flying hours. After extensive testing, Cessna engineers identified several critical fatigue areas that were not being monitored at that time. In addition, Cessna recommended three specific structural modifications, all of which were approved by the USAF and allowed the T-37B fleet to achieve the target 15,000-hour service life. In 1988, almost 20 years later, the USAF completed a durability and damage tolerance analysis and determined that

the T-37 fleet was flying at risk [18]. Later in August of 1989, with many T-37 aircraft approaching the 15,000-hour limit, Sabreliner Corporation was awarded a contract to design and implement a SLEP that involved the modification of four major structural components that included: (1) the forward lower wing spar, (2) the fuselage forward carry-through structure, (3) the horizontal stabilizer and (4) the horizontal stabilizer support structure called the banjo fittings. The objective of the T-37 SLEP was to extend the life of the T-37 fleet such that it would be inspection-free in the SLEP-modified areas for at least an additional 8,000 flight hours. Southwest Research Institute (SwRI) served as principal subcontractor responsible for most of the engineering work performed during the T-37 SLEP. SwRI identified and ranked the T-37 FCLs in the SLEP-modified areas of the aircraft. As a result, the majority of the FCLs originally documented by Cessna Corporation were eliminated. The concluding remarks of the report indicate that:

> The SLEP full-scale aircraft durability and tolerance testing, together with the SLEP damage tolerance analysis, demonstrated that all modified areas would be inspection-free for at least 8,000 flight hours. [18]

During the 1990s, six T-37 aircraft were instrumented with flight load data recorders (FLDR) in an effort to characterize the way these aircraft were being flown in the Undergraduate Pilot Training, Instructor Pilot Training, and Euro-NATO Joint Jet Pilot Training programs. The data from the FLDRs was used to update the SLEP damage tolerance analysis performed in October 1998 and indicated that the 8,000 flight hour inspection-free goal was still being met in most SLEP FCLs. The following table shows a compilation of the FCLs identified in the 1998 SLEP study (Figure 2.13).

2.6.5 T-37 ASIP. The ASIP master plan was developed for the T-37 aircraft and is revised annually by Ogden Air Logistics Center [60]. The purpose of the ASIP master plan is to define and document the specific approach to accomplish the various ASIP tasks throughout the life-cycle of each individual flight vehicle [60]. The plan depicts the time-phased scheduling and integration of all required ASIP tasks for design, development, qualification, and tracking of the airframe. The plan includes

FCL	FCL Description	Material	Appendix A Figure Number
CT11	Wing Fitting Center Lug Edge	7050-T74 die forging	A-3, A-4
W6	Strap Lug Radius	4340 Steel	A-2
W1	Spar Cap Edge @ WS 55.76	7075-T73511 extrusion	A-1
W4	Strap Lug Hole	4340 Steel	A-2
E2	Edge at Top Stabilizer Attach Holes in Forward Banjo Fitting	7175-T74 die forging	A-6
W3	Spar Leading Edge Attach Hole @ WS 57	7075-T73511 extrusion	A-1
CT1	Wing Fitting Center Lug Holes	7050-T74 die forging	A-3, A-4
W2	Spar Cap Hole @ WS 55.76	7075-T73511 extrusion	A-1
W5	First Strap Hole	4340 Steel	A-2
W7	Edge of Strap Below First Attach Hole	4340 Steel	A-2
CT2	Hole at Lower Inboard Wing Fitting Radius	7050-T74 die forging	A-3
CT5	Hole in Center Carry-Through Caps @ BL 0.0	2024-T3511 extrusion	A-5
6B	Wing Rear Spar Lower Cap Fitting	7075-T6 extrusion	A-7
6D	Wing Rear Spar Lower Cap @ Strap End	7075-T6 extrusion	A-8

Figure 2.13: T-37 SLEP FCL List [18]

discussion of unique features, exceptions to the guidance of military handbooks and the associated rationale, and any problems anticipated in the execution of the plan. The development of the schedule considers all interfaces, the impact of schedule delays (e.g., delays due to test failure), mechanisms for recovery programming, and other problem areas [60].

The success of ASIP was demonstrated when the initial 8,000 hours service life of the T-37B aircraft was consecutively increased to 15,000 hours and ultimately to 18,000 hours; more than twice the original service life [60]. As previously mentioned, the first fatigue tests and analysis on the T-37 A/B aircraft were conducted in the 1960s. The study focused on fatigue analysis of the wing, main landing gear, and support structure. The early goal was to establish an 8,000 hour safe-life with a scatter factor of two. However, early in the ASIP program the goal was increased to 15,000 safe-life hours using a scatter factor of two. This was further revised to 15,000 safe-life hours using a scatter factor of four. With the current program of inspections and modifications, the T-37 aircraft can safely reach a service life of 18,000 flying hours [60].

Recently, the ASIP recommended a sonic load analysis be performed on the T-37 aircraft to identify any potential problem areas [60]. A sonic load analysis is a test procedure to determine the effects of sonic fatigue reaction on the aircraft structure. Such fatigue is caused by a magnification of the stresses due to noise operating at or near the frequency of the structure. A sonic investigation of the T-37B was made and compared to the YAT-37D. A problem, consisting of cracking rib flanges in the horizontal stabilizer, was attributed to sonic fatigue. The proposed ASIP modification resulted in retrofitting the aircraft with horseshoe clips. X-ray inspections validated the effectiveness of this modification, which was then incorporated to the entire T-37 fleet. Put in other words, aircraft monitoring programs such as the SLEP and ASIP have proven to be successful in elongating the life of aging aircraft. The goal of the ISHMS is to provide a similar outcome while minimizing costs and maximizing safety of flight.

2.6.6 A-37 SAFE-LIFE. Most of the information presented on the previous SLEP and ASIP sections were based on documentation that the thesis team found on the T-37 aircraft. As previously stated, even though the initial thesis target was the aging A-37 fleet of the CAF, the thesis team had to re-direct the efforts and broaden the scope of the thesis due to limited information availability and accessibility. However, the thesis team did find one document that was relevant to the initial target and is briefly summarized in the following paragraphs. Safe-life is a concept that incorporates margins of safety based on probabilistic data to allow an aircraft be operated to the design life limits without having to conduct fatigue crack inspections [54]. In December 2002, representatives from 12th Air Force asked MAPA to organize an effort to determine the flying hours remaining on a number of A-37 aircraft owned by the CAF. The primary focus of the NDIs was to determine the structural condition of the CAF A-37 aircraft. However, according to the report, the lack of data from CAF flight spectrum prevented a safe-life or damage tolerance assessment [54]. Basically, the engineering team could not collect enough statistical data to accurately quantify initial or recurring inspection intervals. The conclusion of this inspection stated that validation of the flying hours left on the CAF A-37 fleet was dependent upon:

1. Quantifying actual operational usage.
2. Establishing external loads and a usage spectrum.
3. Identifying FCLs and stress spectra through finite element modeling (FEM) analysis.
4. Determining crack growth rates and critical crack sizes.
5. Determining initial and recurring maintenance inspection intervals.

Once the operational usage is known, external loads and a usage spectrum can be developed, identifying FCLs and stress spectra through FEM analysis. The analysis also indicates that along with material and crack growth properties, crack growth rates and critical crack sizes need to also be determined and incorporated into

the model [54]. The findings of this investigation were carefully considered during the development of this thesis.

2.7 Background on Systems Engineering Process

Buede states "engineering involves the practice of applying scientific theories to the development, production, deployment, training, operation and maintenance, refinement, and retirement of a system or product and its parts" [17]. Systems engineering discipline is focused on how to create a system that meets or exceeds the needs of all of the stakeholders involved over the life cycle of the system. The International Council on Systems Engineering defines Systems Engineering as "an interdisciplinary approach and means to enable the realization of successful systems [3]." The stakeholders of the system determine the objectives of the system to which the success of the system is measured. These objectives usually include cost (cheaper), schedule (faster), and technical performance (better). The systems engineer's role is to minimize the problems associated with resolving these conflicting objectives.

The systems engineer can use different methods to apply the interdisciplinary approach for the design and integration process by using the Vee model. The Vee model can also be used incrementally. The processes are iterative. The development of the system can produce individual subsets that are eventually expanded until the entire system is fully operational. The systems engineering Vee model starts with understanding the user requirements to develop the system concept and validation plan (Figure 1.3). This step begins the requirements decomposition and definition portion of the model. It is similar to peeling an onion with each layer revealing the required specifications for the system. Once the onion is fully peeled, the next step is to develop the system performance specifications, system requirements, and the system validation plan. At this point, the systems engineers must help facilitate the design and system tradeoffs due to the complexity of the issues and the multitude of stakeholders involved. The systems engineers then expand the performance specifications into the configuration items (CI) and *design-to* specifications and establish the

CI verification plan. At this point, the systems engineer works with the discipline (design) engineers (e.g., electrical, mechanical, etc.) to evolve the *design-to* specifications into *build-to* documentation and inspection plan. By isolating design decisions using logical engineering principles to decrease development costs, the systems engineer can justify spending the required amount of money to incorporate systems engineering into the total system design and function [17].

The right-hand side of the Vee depicts the integration and qualification activities of the engineering of a system. Moving up this side of the Vee begins with the fabrication, assembly, and coding to the build-to documentation. Integration involves the assembly of the CIs into components, the assembly of lower-level components into higher-level components, and the assembly of high-level components into the system. This involves testing (or qualification) of the newly assembled system elements to determine whether the assembled element meets the set of requirements or specifications that the design phase had established for that element; this qualification is called verification. Verification addresses the following question: Did we build the system right? Once the system is verified against the system requirements, the system must be validated. Validation answers the questions: Did we build the right system? Or does the system meet the user requirements? The systems engineer must demonstrate and validate the system to the user validation plan. After validation, the stakeholders determine whether the system is acceptable [17].

An additional systems' engineering model that can be used is the waterfall model. "The waterfall model is characterized by the sequential evolution of typical life-cycle phases, allowing iteration only between adjacent phases [17]." However, this model has a major problem because the iteration between the phases is often too widely separated. The final model for systems engineering, which is primarily used for software development, is the spiral model. This model has four major processes starting with design, to evaluation and risk analysis, followed by the development and testing, with the final step being planning with stakeholder interaction and approval. The number of iterations of the spiral process can vary. The spiral model can also be

used as a basis for rapid prototyping to produce early, partially operational prototypes. The use of these operational prototypes by stakeholders generates new and improved requirements, as well as provides the stakeholders with increased functionality via early releases of the system [17].

The model that is most appropriate for the ISHMS is the Vee model. The model encompasses the system's operational concept and details three separate architectures (functional, physical, and operational). "The functional and physical architectures are developed in parallel to enhance the integration of them into the operational architecture [17]." The functional or system architecture is the focus of this thesis. Once the requirements are known, the functional architecture can be developed. There are several types of requirements that are used to define the problem. They include mission requirements, originating requirements, and derived requirements. Mission requirements are requirements that are stated in terms that the stakeholders can understand and that show the tradeoffs between doing tasks cheaper, faster, and/or better. The originating requirements are requirements that are focused on constraining system characteristics to achieve the mission requirements [17]. These requirements are established by the stakeholders. Systems engineers use a design process that develops the requirements that define the problem while balancing the dividing the physical resources of the system into components that will meet the requirements by performing certain functions to solve the design problem. Systems engineers must be aware during this stage how each decision can have an affect on the performance and cost of the overall system. The key points concerning the systems engineering design process are:

1. Stakeholders have originating requirements that, taken together address every phase of the system's life cycle. Capturing the complete set of originating requirements ensures a concurrent engineering process.
2. The set of originating requirements should ensure a decision-rich design process by not over constraining the design. The following attributes of requirements

are meant to ensure the process is not overconstrained: traced, correct, unambiguous, understandable, design independent, attainable, comparable, and consistent.

3. At the same time the originating requirements should not underconstrain the design because the stakeholders should be happy with the system that is created. Complete, verifiable, and traceable requirements should guarantee this [17].

Finally, the derived requirements are even more constraining but are developed from establishing the system specifications. "Requirements are the cornerstone of the systems engineering process [17]." This is because requirements define the design problem. Having accurate and *good* requirements are crucial to producing a successful system that meets the stakeholders' needs.

The next step in the systems engineering process is to define the operational concept. "The operational concept of the system provides the theme for the system as viewed by the stakeholders and defines scenarios depicting how its users will employ the system and how the system will interact with other systems [17]." The operational concept for this thesis is to develop an ISHMS for any aging aircraft. ISHMS is defined as an integrated monitoring system that is incorporated into the overall aircraft systems (e.g., electrical, mechanical, etc.) to determine the overall structural health of the system by detecting any anomalies in the critical fatigue structural areas of the aircraft while maintaining or increasing the level of safety of flight. This system will be cost-effective and provide *real-time* data to the pilots and maintainers for analysis.

An external systems diagram must be developed to show the interaction between the inputs and controls that enter the system, as well as outputs that the system produces, and the mechanisms that are used to transform the inputs into the outputs. Systems engineers must also concern themselves with the systems relevant to every stage in the life cycle of the system throughout the entire development process. After developing an external systems diagram, an objectives hierarchy of the system must be developed to determine the criteria that the stakeholders will measure their satis-

faction of the system performance, cost, and development schedule. Ultimately, the systems engineers must work with the stakeholders to conduct performance, cost, and cost-performance trade-off studies. The final step of integration and qualification is acceptance by the stakeholders. The stakeholders compare the system to their needs and decide if they will accept the system as is or if changes will need to be made. The completion of this phase indicates that there is at least one feasible solution that will satisfy the stakeholders' needs and is verified and approved by the stakeholders [17].

III. Methodology

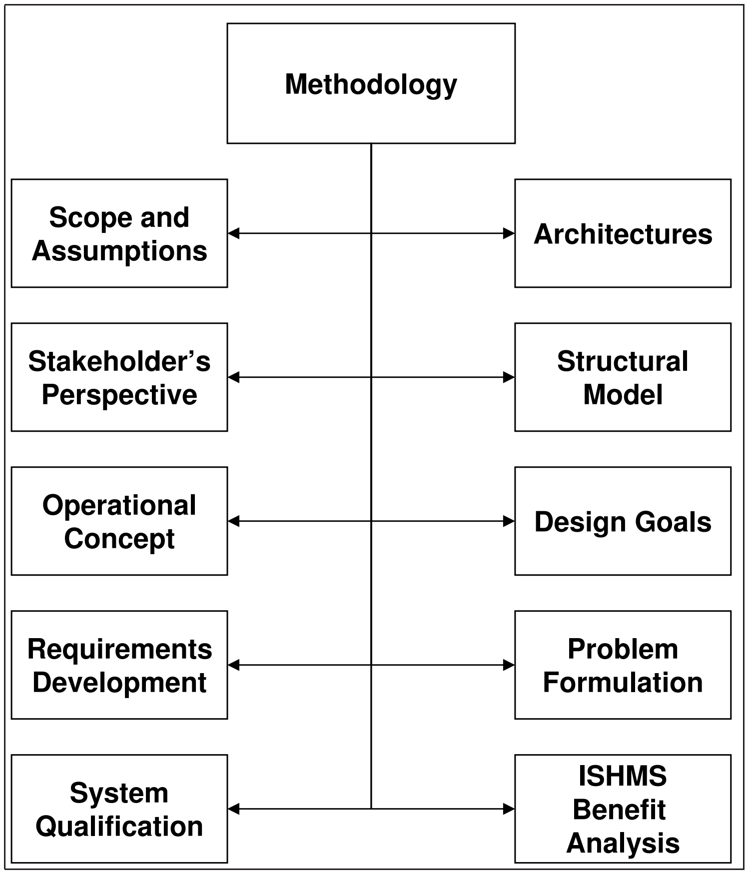

Figure 3.1: Chapter 3 Decomposition

In this chapter (Figure 3.1) the methodology used in order to deal with the problem of this thesis is discussed. The scoping of the problem is explained and the basic assumptions detailed. The steps of the system engineering methodology are discussed and the methods to define the stakeholders' perspective and the operational concept are presented. The development of the system requirements and the various architectural products is analyzed. The chapter concludes with a detailed explanation of the material analysis and crack growth modeling used in the simulations which helped to show the potential benefit of an ISHMS.

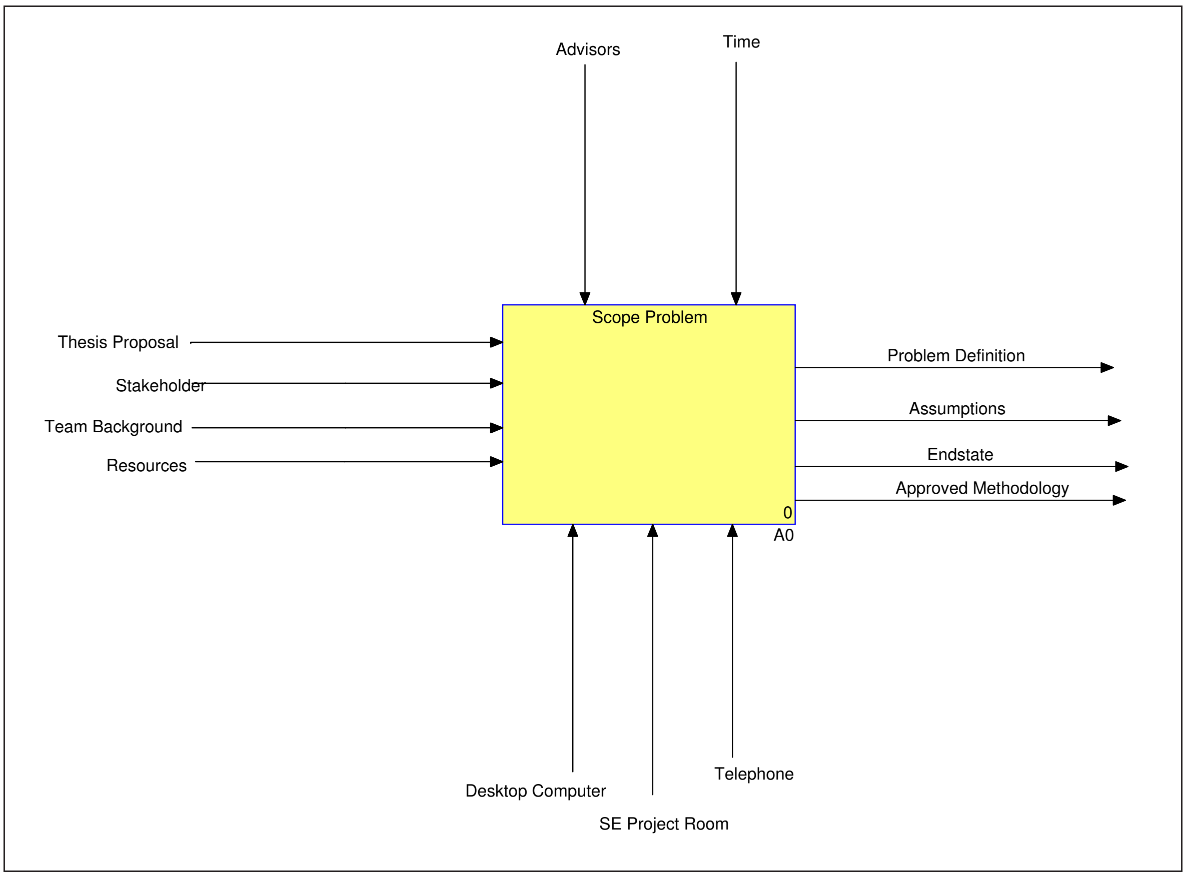

Figure 3.2: Problem Scope

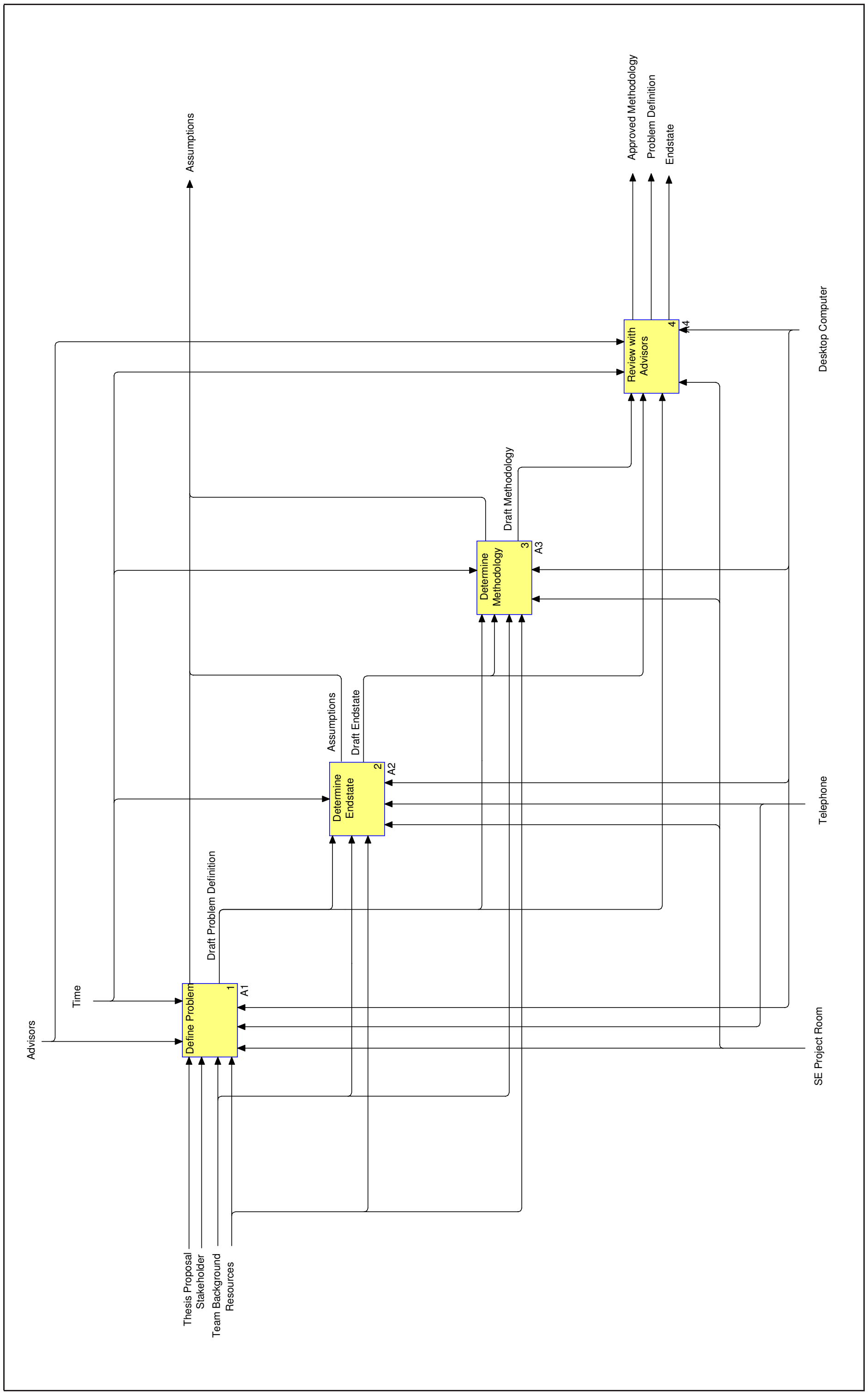

Figure 3.3: Problem Definition

3.1 Scope and Assumptions

3.1.1 Scope. In order to develop a systems engineering approach to establishing an ISHMS that can be applied to any aging aircraft, the thesis had to be adequately scoped to provide a realistic example. SAF/IARL originally contacted AFIT/ENY to request a thesis be accomplished to determine how real-time integrated health monitoring could be accomplished for the aging A-37 aircraft used by CAF. The thesis proposal stated that these CAF A-37 aircraft have very high flight hours and are approaching or have already exceeded the originally designed service life. Their primary concern came from finding structural cracks during scheduled inspections. However, there is no current system on the CAF aircraft that could detect new cracks on the structure or detect if the current cracks, which are within acceptable limits, grow. The original goal of the thesis proposal was to develop a systems engineering approach to design a system that would monitor the structural health of the CAF A-37 airframe. By developing and implementing a monitoring system, the CAF air forces aim was to reduce or eliminate extensive inspections and safely extend the original designed service life. However, when the thesis team tried to obtain maintenance history on these CAF A-37 aircraft, the team found that the necessary maintenance data was not available. Therefore, the thesis sponsor suggested contacting the Mature And Proven Aircraft (MAPA) division at Hill Air Force Base, Utah to obtain the data on the top 10 locations on the A-37 aircraft identified as showing signs of critical fatigue. The MAPA division had assessed critical structural nodes, otherwise known as FCLs, over the entire aircraft to determine which locations needed to be monitored to maintain the same safety of flight standards after the aircraft passed its designed service life limit. To scope this thesis to an achievable goal, the thesis team narrowed its focus to developing a systems engineering approach to designing an ISHMS for any aging aircraft but using the A-37 aircraft data provided by MAPA to determine the FCLs. The ISHMS team chose to analyze the number one FCL.

The sponsor also requested cost estimates for installing a real-time, integrated structural health monitoring system. Another aspect of scoping the problem was to

determine that only the user of the system could determine the definition of *real-time* and that the team would incorporate the request in the user's requirements of the systems engineering process for an ISHMS that is developed. The sponsor also requested cost estimates for installing a monitoring system. The ISHMS thesis team concluded that it does not have the expertise to establish specific cost estimates for developing, designing, and installing an ISHMS. It is not the responsibility of the systems engineer to determine costs, instead it is his/her responsibility to work with the design engineers to meet the user requirements and therefore eventually the cost estimates will be available. The ISHMS thesis team does have limited expertise in certain areas. Three team members are experienced Aircraft Maintenance Officers, two members are mechanical engineers, one member is an aeronautical engineer, and one member is an electrical engineer.

Over the period of the thesis, the primary individual sponsor moved to a different job and the team could not find an additional sponsor that would fund the original request. Another limitation of this thesis was the time that was available to conduct the data collection, analyze the data for the FCLs, and develop a systems engineering approach that can be applied to all types of aging aircraft. Due to the limitations of losing our sponsor, our advisors took an active role in guiding and focusing the team.

3.1.2 Assumptions. There are a number of assumptions that were required to develop the systems engineering process to develop an ISHMS. They are:

- Appropriate technology has already been developed to monitor all of the FCLs.
- Equipment can be developed to capture the data from the sensors on the FCLs
- Enough maintenance history data will be available on any aging aircraft that an ISHMS will be implemented
- The total life-cycle cost of the system is lower than the current maintenance practices
- The ISHMS will maintain or increase the SOF for that specific aircraft.

- Installation of the monitors on the FCLs will not cause additional damage
- Maintenance technicians can be trained to download and analyze the maintenance data

The methodology used to define the system's stakeholders is described in the next section. Also, the methodology used to develop the system's operational concept is discussed.

3.2 Stakeholder's Perspective of the System

An important step at the beginning of the design of a system using the Systems Engineering methodology is to identify the stakeholders. As it is stated in the relevant literature the more generic term *stakeholders* is preferred over the term *users* because the term can describe multiple categories of users.

Some of the users categories are the bill payers, the developers, the operators, the trainers etc. Each of these categories is involved in different ways at different phases of the system's life-cycle, so the use of term *stakeholders* can better describe these differences than the term *user*.

As a result of the different ways the various stakeholders are involved in the systems life cycle, each stakeholder has his own understanding and view of the system. Depending on his/her role, the perception of the system design, development, production, use, maintenance, retirement may differ significantly from the other stakeholders.

According to the systems engineering methodology it is important for the systems engineer to identify (early in the process) all the stakeholders involved with the system under development. It is also important that the engineer work with those stakeholders and get a thorough understanding of each ones perspective and requirements. The importance of these actions lies in the fact that all stakeholders' views and requirements are equally significant. There are not views and requirements that are *right* or *wrong* and the perspective and requirements of a specific stakeholder are

not more significant than another's. If the stakeholders are not properly defined some requirements for a phase of the life cycle may not be addressed during the design. This will result in an incomplete design.

It is the systems engineer's role to work with all the stakeholders and based upon their inputs to establish priorities, and to specify the final product's design: the one that will satisfy all mandatory requirements and will address as many of the stakeholders' views as possible.

In order to identify the stakeholders a critical question that must be answered is *who has the right to have a requirement for the system?* [17]. Based on the answer to the above question a *system requirements team* comprised of the systems engineers and representatives of all the stakeholders categories is formed. Their goal is to derive the operational concept and the originating requirements.

For the purpose of this thesis, the group members and the academic advisors decided to have both the roles of the systems engineers, who are supposed to identify all the stakeholders and form the system requirements team, and of the stakeholders, who are supposed to provide the systems engineers with their operational needs and their requirements. The factors that led this team to this decision were: the available time for the elaboration of this thesis, the lack of specified stakeholders to work with and the need to have a wider and more flexible scope for our problem. All these factors were critical in conjunction with each other. The thesis team had to keep the scope of our problem wide and flexible enough so that the thesis would be able to show the applicability of the systems engineering methodology to the design of the ISHMS. In order to achieve this goal the thesis had to define the stakeholders' needs and requirements that would be used as a basis for the development of the system's architecture. All that had to be accomplished within a specified period of time and with additional constraints as to the availability of the team members.

The group members felt that the most appropriate way to achieve the thesis goals given the above constraints would be to create a list of the ISHMS life-cycle

phases and try to identify the stakeholders for each phase. This identification of potential stakeholders was based on the diverse professional experience of the group members. Also, based on the same experience and knowledge, the group members tried to understand and describe each of the stakeholder's view and requirements. The final product, which is a set of assumptions, has not been validated, and restricted the development of the originating requirements document.

3.3 Operational Concept of the System

The development of the operational concept is another essential step in the systems engineering process. By the term *operational concept* a description of the way the system will be utilized is implied. In this description of the system's utilization, a vision of the system, its interactions with external systems and the main functions of the system are included. An important aspect of the operational concept is that it represents the agreement between the various stakeholders about the use of the system and the needs it is going to serve. Usually the operational concept is written in the stakeholders' informal language. It is the systems engineers' role to bring the stakeholders to this agreement and produce the operational concept. The understanding of each stakeholder's vision for the system and the system's mission requirements are essential.

In order to define the operational concept there are several methods the systems engineers can apply:

- A set of scenarios that describe the inputs to the system and the produced outputs at the various phases of the life cycle, is one way to develop the operational concept. In these scenarios, the system is treated as a *black box*. That means that only the inputs and outputs of the system are shown; the transformation that occurs within the system is not visible. This allows the operational concept not to influence and *steer* the system's design. In each scenario the view of a stakeholder about the production, use and maintenance of the system is

shown. The scenarios are developed separately for each life-cycle phase and are as many as to address all stakeholders groups that are involved in the specific phase. These sets of scenarios describe the reason for the system's existence and result in the development of *an operational concept for each life-cycle phase*.

- A variation of the above method is the method described by Hunger [17]. The term mission analysis is used by Hunger instead of the term operational concept and the scenarios are called missions. The life-cycle phases of the system are divided into operational and non-operational phases for which sortie and life missions are generated respectively. Missions are developed for each life-cycle phase while some scenarios may extend to more than one phases. These missions provide information about the system's interaction with other systems and define the system's boundaries.

- Another method that can be used to produce the operational concept is the development of use cases. The concept of use cases is more related to the software engineering, but there is no limitation to their use in systems engineering. The use cases are similar to the sets of scenarios but are differently structured than the scenarios. The main difference is that the use cases are developed using a specific goal as a basis. Variations in the use cases around that basis help describe the different views of the stakeholders. The use cases can then be used in the derivation of requirements.

- The input-output trace modeling technique can also be used in the development of the operational concept. The model produced from this technique consists of a vertical time line for each system involved in the scenario. Horizontal arcs starting from the originating system and ending at the receiving system depict the systems interactions. These models are focused on time based interactions between the systems. Their advantage over the written scenarios is that they provide a visualization of the sequence of actions which can be more helpful during the system design.

- Using the same concept as the input-output trace model the sequence diagrams provide another modeling option that can be used in the development of the operational concept. The sequence diagrams used in the Unified Modeling Language (UML) have a lot more complexity than the input-output trace diagrams but are also more explicit.

In order to develop the operational concept, the thesis group decided to create sets of scenarios for the life-cycle phases of the system. The scenarios are developed with the key stakeholder for each phase as the main *actor*. The other stakeholders are also included in the scenario as needed while other constraining and complexity factors are added in the scenario. Another reason for the selection of this method is that, according to the thesis group members' understanding, the sequence diagrams, the input-output model and the use cases would require a greater involvement of the stakeholders. Therefore the creation of scenarios seemed more suitable. Some aspects that the thesis' methodology was not able to achieve are the validation of the scenarios and *the agreement between the stakeholders* aspect of the operational concept.

In the next section, the development of the systems requirements is discussed. The assumptions made by the thesis group, and the detailed steps of the selected approach are analyzed.

3.4 Requirements Development

Manpower intensive periodic maintenance inspections were driving up the cost of operating legacy aircraft. An ISHMS was proposed as a solution to reducing the cost of legacy aircraft operations. The constraints imposed on the design space were:

1. Legacy aircraft use would continue at its current pace
2. ISHMS would be retrofitted to the legacy aircraft
3. Current SOF would be maintained

The effective impact of the constrained design space was to bypass the initial business case in favor of monitoring (versus repair or replace) the legacy aircraft.

This was the starting point for a systems engineering approach to the development of an ISHMS. The ISHMS development process began with the requirements definition. The requirements definition was the baseline with the final system was compared with to determine if a successful design was created. Requirements were the cornerstone of the systems engineering process and the focal point of the ISHMS development [17]. Many of the requirements resulted from working within the physical constraints of the legacy aircraft. The SE creation of an ISHMS on a legacy aircraft design yielded a less streamlined and integrated solution than would be possible with a new aircraft design. All phases of the ISHM system life-cycle were addressed (Figure 3.4).

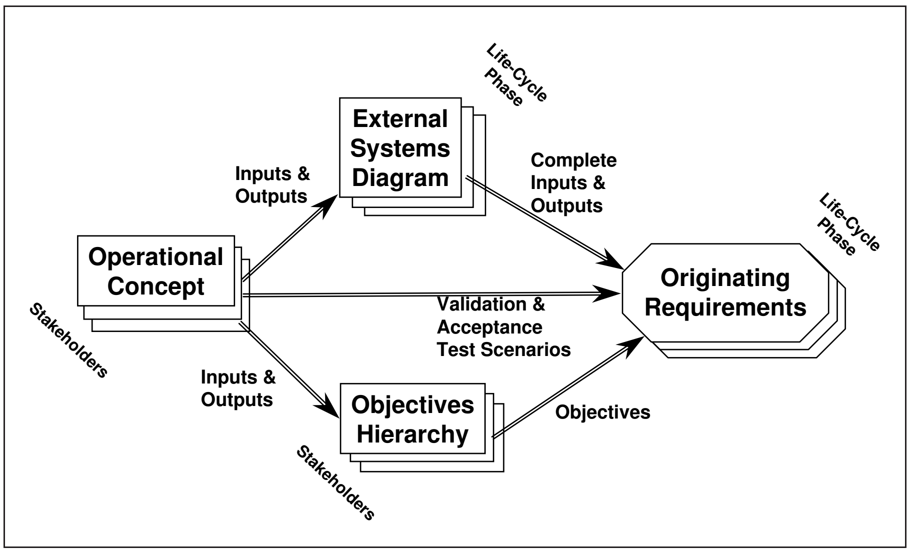

Figure 3.4: Originating Requirements Development Summary [17]

Assumptions were made to quantify the current aircraft flight profile, current maintenance inspection costs, and to estimate installation costs. Flight data recorder information was not available; therefore, a general fighter flight spectrum was used. The baseline inspect and fix scenario was compared to the ISHMS modified scenario to show improvement in operating cost. The ISHMS team had limited sponsor feedback, thus based upon field experience team members served as stakeholders to clarify the initial requirements as well as the SE to refine the requirements. There were many stakeholders across the ISHMS life-cycle phases, but the primary stakeholders referenced were: HQ AF, pilots, maintainers, and acquisition personnel.

The method for creating the ISHMS requirements involved a seven step approach:

1. The first step consisted of developing the operational concept. The operational concept created a general vision of the system, a statement of capability (or mission) requirements, and how the system was expected to be used. The operational concept was given by the sponsor.
2. The second step was the definition of the system boundary with an external systems diagram (Figure 3.5).

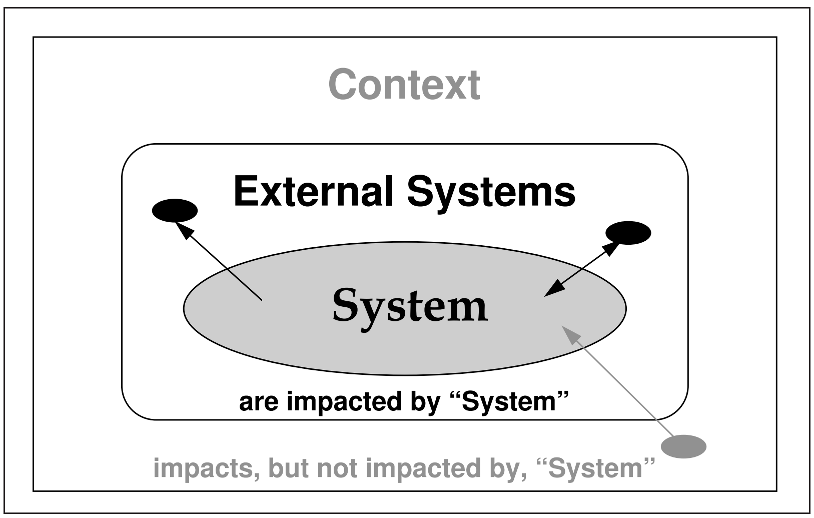

Figure 3.5: Context Diagram [17]

3. The third step was the development of the weighted objectives hierarchy. This hierarchy defined cost, schedule, and performance goals that the stakeholders required for an acceptable system design (Figure 3.6).
4. The fourth step of developing, analyzing and refining the requirements required taking the operational concept, system inputs and outputs, and combined with the objectives hierarchy to refine the originating requirements into the system requirements.

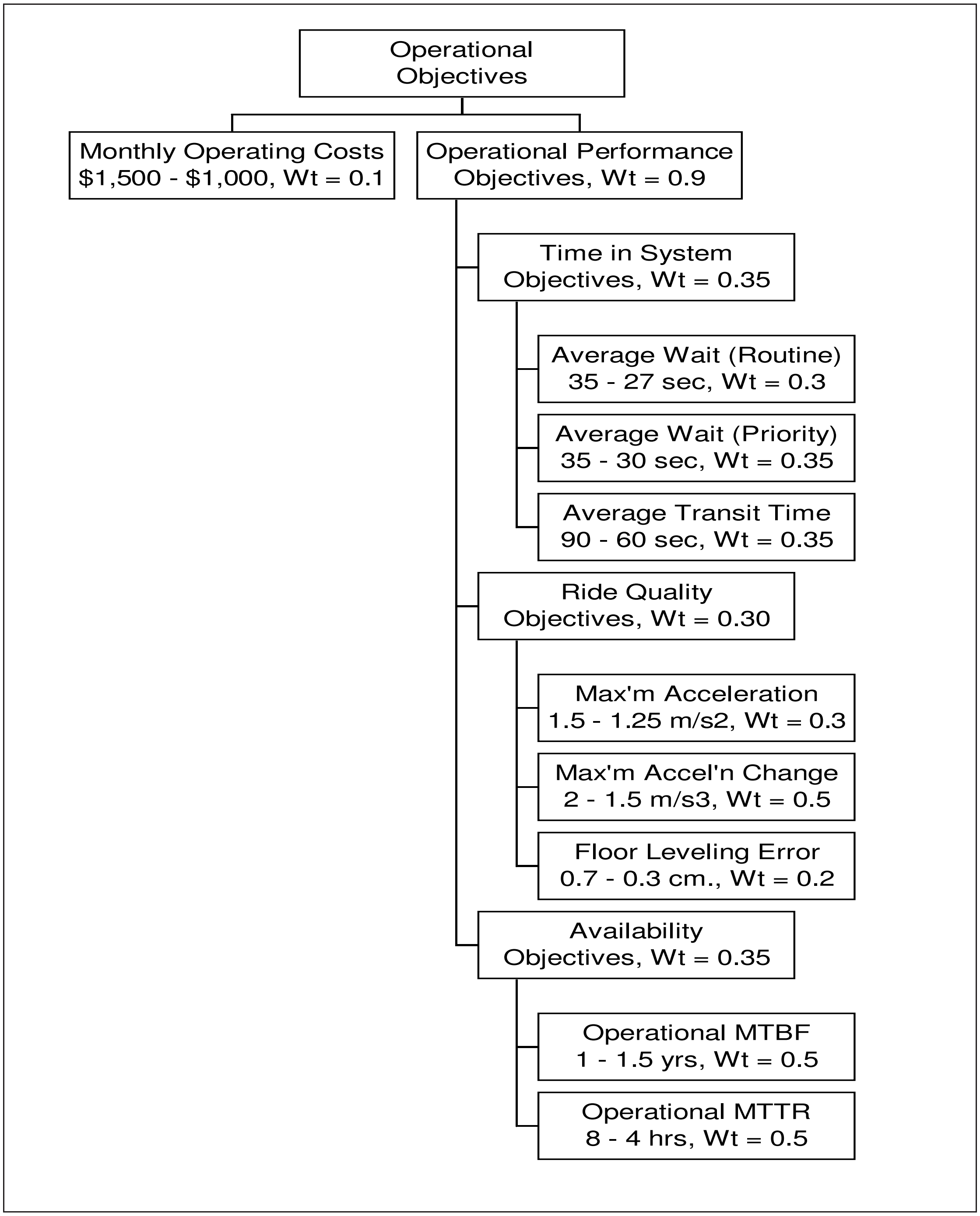

Figure 3.6: Objectives Hierarchy Example [17]

5. The fifth step was to ensure the requirements feasibility. Feasibility was determined if the requirement was verifiable with physics-based modeling, consistent with general maintenance practices, or testable.
6. The sixth step was defining the qualification system requirements. The system qualification involved establishing the requirements to; validate the operational concept, verify the components & system, validate the system, and accept the system. Extensive structural modeling and simulation was conducted of the A-37 aircraft to qualify the system requirements (Figure 3.7).
7. The seventh and final step was obtaining the sponsor approval of the requirements.

The Buede process of establishing the ISHMS requirements was chosen because of its structured method [17]. This structured approach was a consistent method for both the originating and derived requirements. Finally, the structured requirements method was compatible with the chosen Vee Model of SE design. In accordance with the Vee model, system requirements became more specific as the development process progressed. The ISHMS requirements were specified down to the third level of the requirements pyramid (Figure 3.8). This meant the mission, originating, and system level requirements were developed. The ISHMS team decided to stop the requirements specification before the subsystem and component level. The subsystem and component level was chosen as the line of demarcation because this was the point where dedicated engineering specialists provide the engineering expertise necessary to establish detailed requirements. Attempts to establish the component specifications will unnecessarily limit the design space.

The requirements process began with the mission and originating requirements. These requirements were the starting point of the ISHMS written by the user. The user input was a capability needs document listing a need for an ISHMS to operate legacy aircraft beyond their original design service life. Ideally, these originating requirements were design independent. In reality, the initial business case was assumed

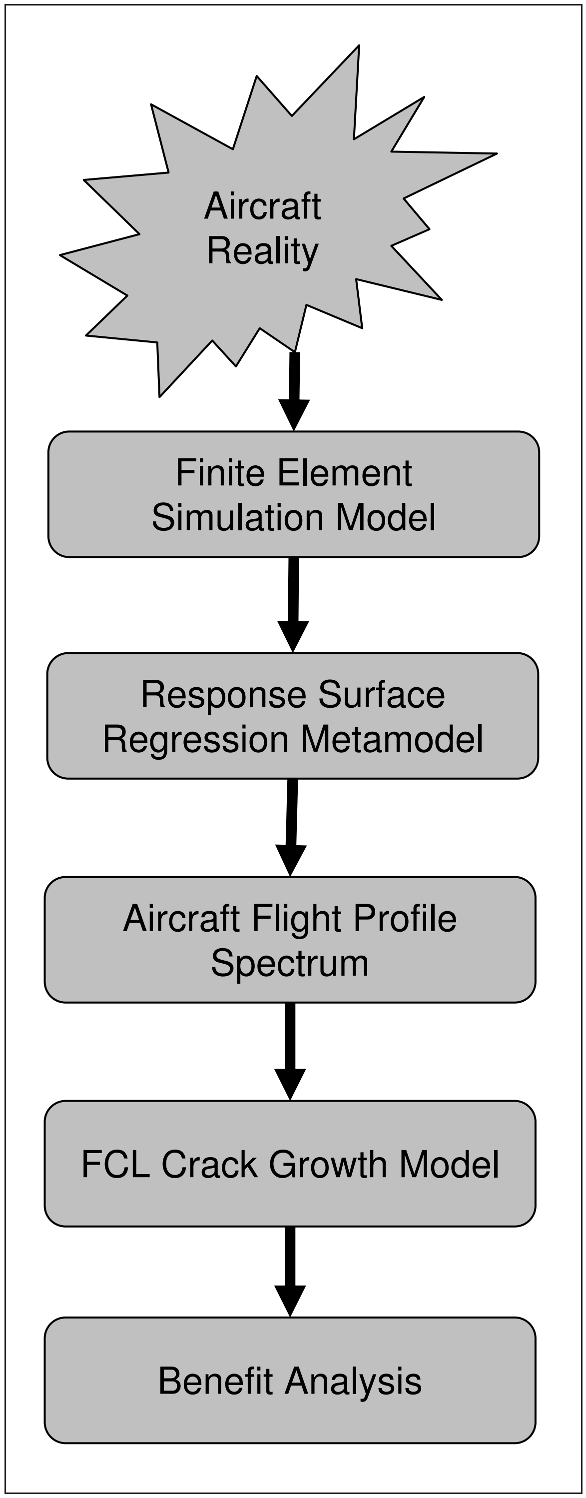

Figure 3.7: Structural Simulation Steps

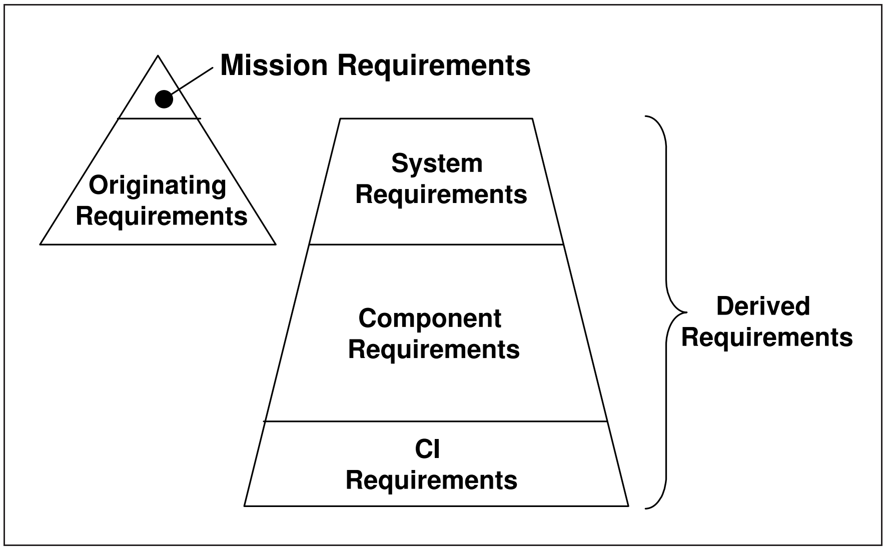

Figure 3.8: Requirements Hierarchy [17]

already completed with the result of modifying a legacy aircraft with an ISHMS as the result. This jump to an ISHMS as the solution to increasing maintenance inspection requirements had an effect of constraining the design space automatically reducing options such as; maintaining the status quo, using automated inspections, or replacing the wing on the legacy aircraft. The initial scoping of the design made the benefit analysis very important to determining if installing an ISHMS yielded an economic benefit.

The design requirements allowed the SE development team to apply a level of engineering rigor to the originating requirements. The design requirements partitioned the design problem. The partitioning of the design problem enabled the establishment of a verification and validation plan. The design requirements were clarified with the stakeholders and trade-space was established.

3.5 System Qualification First Look

Before beginning preliminary design, system engineers should consider how the system requirements will be verified. This thesis analyzed each system requirement and briefly detailed how each would be tested or verified for qualification. The analysis

done for this thesis does not constitute a full-up qualification or verification test plan. The analysis assisted in showing requirements feasibility and could assist others following the systems engineering process presented here with preparations for their own qualification testing.

Verification of requirements can generally occur through four types of methods: inspection, analysis and simulation, instrumented test, and demonstration. This thesis selected the appropriate method for each requirement. Of course, this analysis occurred prior to design which does not allow for tailoring testing toward the specifics of the system. As stated, the initial qualification review would be revised after system design to best test and verify the system as designed.

The architectural framework and the architecture building process are discussed in the next section. The methodology for selecting which architectural products, and how they will be developed is analyzed. Also, assumptions, tools and the rationale for this selection are discussed.

3.6 Architectures

Aircraft come in various shapes and configurations which are mostly determined by the intended role or roles of the aircraft. However, all aircraft have at least one thing in common and that is an intrinsic complexity which is carried through all of the life-cycle stages (i.e., development, production, operations & maintenance, and retirement). This complexity not only comes from the thousands of components and specialized parts that must work together for the aircraft to function properly, but also from the various external systems that are needed to support the aircraft operations. Examples of external systems include personnel, tools, equipment, and other support systems, for instance global positioning system (GPS) satellites for navigation purposes. In the midst of this complexity, the systems engineer is expected to provide clarity and simplicity needed for efficient and effective decision-making.

The necessity for understanding and dealing with complex system interactions is particularly applicable to USAF aircraft because a single decision may have far-reaching implications into multiple systems and organizations. Often times, system engineers use architectures as one of the preferred SE means of providing clarity and simplicity to complex systems. Architectures, as defined in SE, are graphical, textual, or tabular representations which are used to display information about a system in a comprehensive way that facilitates decision-making [26]. The goal of this section is to explain how system architectures were used to model the potential development and integration of a hypothetical ISHMS into an aging aircraft. In addition, this thesis will also explain the reasons for choosing specific architecture products as well as the guidelines used for the development of the architectures.

System architectures come in different shapes, forms, and perspectives based on the team's decisions and on the personal preferences of the architect. However, even though this flexibility in creating system architectures may promote innovation, it also has the potential to further confuse the decision-makers that generally come from different backgrounds. Fortunately, the DoD realized that lack of architectures standardization may lead to miscommunication, or even worse, lack of communication between stakeholders and developers. As a result, the DoD generated a standardized solution which is now known as the DoD Architecture Framework (DoDAF). The DoDAF, along with several other documents, provide guidelines and policies for the development of system architectures within the DoD and is the source document for the development of the architectural products.

3.6.1 DoD Architecture Framework. According to the DoDAF, an integrated architecture is usually described in terms of three views: Operational View (OV), Systems View (SV), and Technical Standards View (TV). Together, these architectural views provide an organized and systematic way to gain understanding, support analysis, provide logic for potential changes, specify requirements, or support

systems level design and integration activities. The following paragraph provides a brief description of each of the views.

The OV contains graphical and textual descriptions of operational activities, or functions, and information exchanges [26]. Similarly, the SV also uses graphical and textual products; however, the emphasis is placed on describing actual systems components and interconnections in support of the functions or capabilities described in the OV. The TV is defined as the minimal set of rules governing the arrangement, interaction, and interdependence of systems parts or elements. The purpose of the TV is to ensure that a system satisfies engineering specifications. Furthermore, the DoDAF also identifies the All Views (AV) products which provide information relevant to the entire architecture but do not represent a distinct view of the architecture [26]. Each of these views has a myriad of products from which the systems architects can choose from. Table 3.1 lists each of those products.

3.6.2 Architecture Building Process. The DoDAF provides a generic six-step process (Figure 3.9) of building an architecture description that was used by the team. The first step was to *determine the intended use of the architecture*. In the case of the ISHMS for aging aircraft, there were two fundamental purposes for creating an architecture description. One of the purposes was to try to identify as clearly as possible the overall requirements that should bound the development of the ISHMS. The second purpose was to support an investment decision as to whether or not the development of an ISHMS for an aging aircraft makes financial sense. Since the target aircraft was the A-37 owned by the CAF, the thesis team wanted to interview their personnel in order to gain insight of the actual user requirements. In addition, the team had hoped to gain a better understanding of their maintenance procedures and their flight profiles among other things which would greatly influence the final ISHMS design. However, the thesis team did not have access to the CAF and as such the thesis team had to collect the requirements from the group's knowledge and experience.

Table 3.1: Architecture products defined in the DoDAF [27]

Applicable View	Framework Product	Framework Product Name	General Description
All Views	AV-1	Overview and Summary Information	Scope, purpose, intended users, environment depicted, analytical findings
All Views	AV-2	Integrated Dictionary	Architecture data repository with definitions of all terms used in all products
Operational	OV-1	High-Level Operational Concept Graphic	High-level graphical/textual description of operational concept
Operational	OV-2	Operational Node Connectivity Description	Operational nodes, connectivity, and information exchange needlines between nodes
Operational	OV-3	Operational Information Exchange Matrix	Information exchanged between nodes and the relevant attributes of that exchange
Operational	OV-4	Organizational Relationships Chart	Organizational, role, or other relationships among organizations
Operational	OV-5	Operational Activity Model	Capabilities, operational activities, relationships among activities, inputs, and outputs; overlays can show cost, performing nodes, or other pertinent information
Operational	OV-6a	Operational Rules Model	One of three products used to describe operational activity identifies business rules that constrain the operation
Operational	OV-6b	Operational State Transition Description	One of three products used to describe operational activity identifies business process responses to events
Operational	OV-6c	Operational Event-Trace Description	One of three products used to describe operational activity traces actions in a scenario or sequence of events
Operational	OV-7	Logical Data Model	Documentation of the system data requirements and structural business process rules of the Operational View
Systems	SV-1	Systems Interface Description	Identification of system nodes, systems, and system items and their interconnections, within and between nodes
Systems	SV-2	Systems Communications Description	System nodes, systems, and system items, and their related communications lay-downs
Systems	SV-3	Systems-Systems Matrix	Relationships among systems in a given architecture; can be designed to show relationships of interest, e.g., system-type interfaces, planned vs. existing interfaces, etc.
Systems	SV-4	Systems Functionality Description	Functions performed by systems and the system data flows among system functions
Systems	SV-5	Operational Activity to Systems Function Traceability Matrix	Mapping of systems back to capabilities or of system functions back to operational activities
Systems	SV-6	Systems Data Exchange Matrix	Provides details of system data elements being exchanged between systems and the attributes of that exchange
Systems	SV-7	Systems Performance Parameters Matrix	Performance characteristics of Systems View elements for the appropriate time frame(s)
Systems	SV-8	Systems Evolution Description	Planned incremental steps toward migrating a suite of systems to a more efficient suite, or toward evolving a current system to a future implementation
Systems	SV-9	Systems Technology Forecast	Emerging technologies and software/hardware products that are expected to be available in a given set of time frames and that will affect future development of the architecture
Systems	SV-10a	Systems Rules Model	One of three products used to describe system functionality; identifies constraints that are imposed on systems functionality due to some aspect of systems design or implementation
Systems	SV-10b	Systems State Transition Description	One of three products used to describe system functionality; identifies responses of a system to events
Systems	SV-10c	Systems Event-Trace Description	One of three products used to describe system functionality; identifies system-specific requirements of critical sequences of events described in the Operational View
Systems	SV-11	Physical Schema	Physical implementation of the Logical Data Model entities, e.g., message formats, file structures, physical schema
Technical	TV-1	Technical Standards Profile	Listing of standards that apply to Systems Views elements in a given architecture
Technical	TV-2	Technical Standards Forecast	Description of emerging standards and potential impact on current Systems Views elements, within a set of time frames

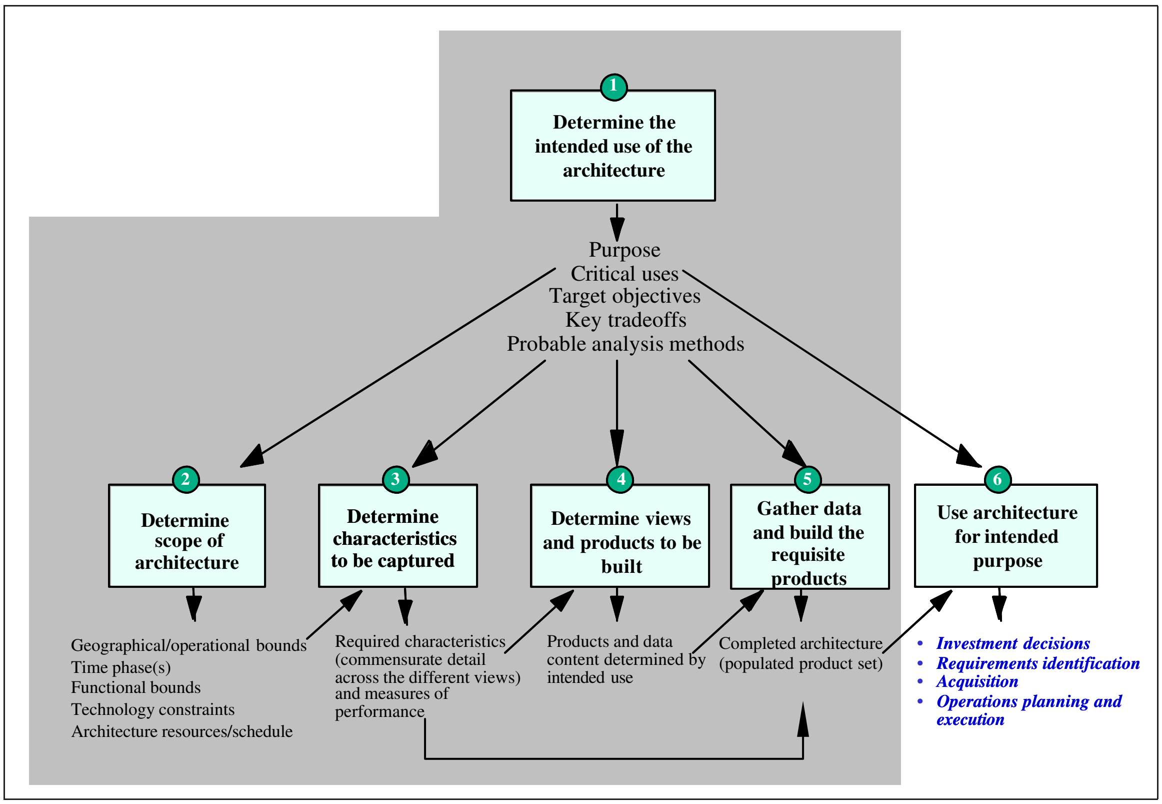

Figure 3.9: Process for Building Architectures [26]

3.6.2.1 Step One. This first step generated many important questions.

- What does the user really mean by integrated?
- Should the ISHMS be a plug-and-play device or should it be networked with various internal aircraft components?
- Should the ISHMS have its own power source or should it be connected to the aircraft's power source?
- Which aircraft structures should be monitored?
- What types of sensors should be used for monitoring?
- How many sensors are required to satisfy user requirements?
- What should be the sampling rate of the sensors in order to satisfy the real-time monitoring system requirement?
- How reliable should the ISHMS be?
- What will be the net result of having an ISHMS in terms of saving money?
- Should the current time between inspections be increased? If so, by how much?
- Should the number of inspection items be decreased? If so, by how many?
- Should the data be stored and downloaded after each flight or will it be monitored in near-real-time?
- Which organizations should be responsible for maintaining and sustaining the system?

These and many other questions form the basis for the architectures. It is important to always keep in mind the user's perspective. Obviously, the user has two primary objectives:

1. To save money by not having to replace their aging aircraft and reducing maintenance costs.
2. To minimize the impact to their operational mission by reducing the current inspection burden.

The system architectures were built with these two objectives in mind.

3.6.2.2 Step Two. Once the purpose and content of the architecture had been established, the second step in the architecture building process was to *determine the architecture descriptions scope, context, environment, and any other assumptions considered*. In terms of scope, the reader is referred to a previous section which is entirely devoted to defining and scoping the problem. However, when scoping the architectures the team was primarily interested in defining the ISHMS mission(s), defining those activities that the user would classify as being necessary functions of an ISHMS, and assigning responsibility to the potential organizations that would have to interact with the ISHMS.

The mission of the ISHMS is to provide a near-real-time structural monitoring of an aging aircraft's FCLs while maintaining or improving the current SOF at an affordable cost. The primary functions that the ISHMS must provide are included in the architecture and will be explained in more detail in Chapter 4. The team had some notional ideas as to which organizations will most likely be tasked to interact with the ISHMS; however, because of our limited knowledge on the organizational structure of the CAF, the architectures only show hypothetical entities. Nevertheless, the task of matching these hypothetical organizations to the real organizations should be fairly straight-forward.

For the most part, the level of detail in the architectures was left intentionally rather broad since the team was only dealing with the initial decomposition and definition leg of the Vee-model. Moreover, the limited user involvement made it impossible to go deeper into defining the physical configuration items of the ISHMS. Future SE thesis groups that have the opportunity to interview or somehow collect user requirements from the CAF will be able to narrow down the system design requirements and perhaps propose a physical solution.

3.6.2.3 Step Three. Step three in the architecture building process is to *determine what information the architecture description needs to capture*. Basically, this step is about making sure that the information displayed in the architectures is relevant and correlates with the information collected from the previous steps. DoDAF explains that "if pertinent information is omitted, the architecture description may not be useful; if unnecessary information is included, the architecture effort may prove infeasible given the time and resources available, or the description may be confusing and/or cluttered with details that are superfluous to the issues at hand." [26]

Several MAPA reports on the ASIP, SLEP and safe-life programs became the backbone of the thesis. However, policies regarding the distribution of foreign information limited and almost prevented further research on the CAF A-37 fleet. After several trials, the only way the team was able to by-pass this obstacle was by making an assumption that the A-37 and the USAF's T-37 aircraft shared similar structural characteristics. Even though initially the team thought that this assumption was a big leap from reality, the list of the top ten FCLs for both aircraft is nearly identical, thus in a way verifying that this assumption is valid. The benefit of this assumption should be obvious. There is more organic information available on the T-37 because it is still in the USAF's inventory. Nevertheless, the team realized that the architectures were limited to a great extent by the information that was available and accessible.

3.6.2.4 Step Four. The next step is to *determine the products to be built*. As previously stated, the DoDAF has a significant number of architecture

products to choose from depending on the needs and preferences of the architect. However, the DoDAF states that "an integrated architecture consists of AV-1, AV-2, OV-2, OV-3, OV-5, SV-1, and TV-1 as a minimum [27]". In addition, DoDAF provides a list of various combinations of applicable architecture products depending on the intended use of the architecture, which are shown in Figure 3.10.

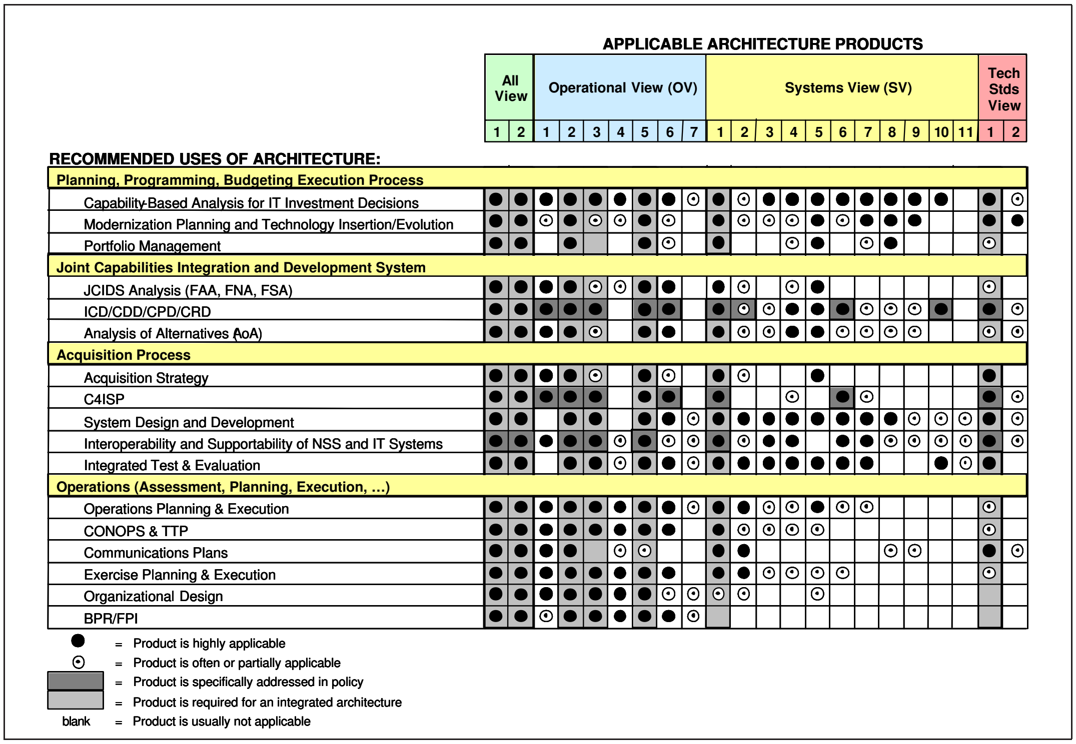

Figure 3.10: Architecture Products by Use [27]

From the list of recommended architecture uses above, only two choices seemed to fit to the project requirements: (1) System Design and Development or (2) an Acquisition Strategy. After some thought, the team decided that it was not feasible for the team to be involved in the physical design of an ISHMS. Instead, the goal was to define and identify possible system requirements and hopefully demonstrate the financial feasibility of incorporating an ISHMS into an aging aircraft. Thus, the team concluded that the architecture products should resemble those of an acquisition strategy. DoDAF suggests the following architecture products for an acquisition strategy: AV-1, AV-2, OV-1, OV-2, OV-5, SV-1, SV-5, and TV-1. Even though there are slight

differences between what policies require and what DoDAF recommends, the team decided to concentrate the efforts on creating the required architecture products first. Any other architectures that the team considered would add value and clarity to the analysis would be generated later. All the architecture products will be presented in Chapter 4. An aspect of system architectures development that may seem confusing is the fact that the sequence of the products does not follow their logical numerical sequence. Even though the actual sequence followed is a matter of preference and convenience, Figure 3.11 depicts the suggested developmental sequence taught in the Air Force Institute of Technology Systems Engineering 640 course. The team adhered to this sequence for the architecture development.

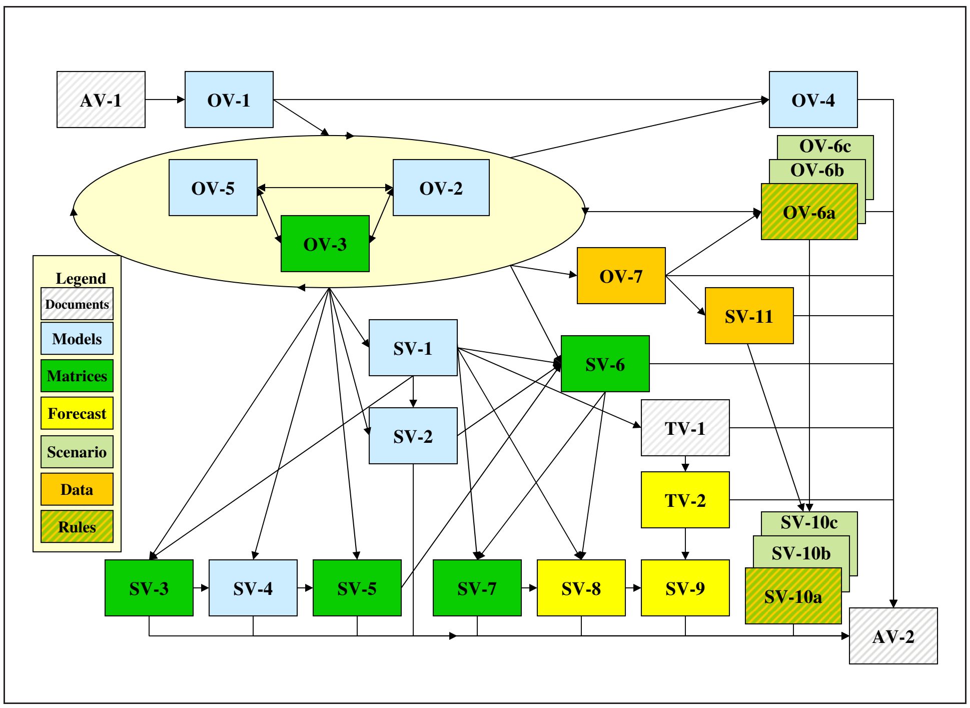

Figure 3.11: Architecture Products Sequence [48]

3.6.2.5 Steps Five and Six. The last two steps of the six-step architecture building process are *gather the architecture data and build the requisite products* and *use the architecture description for its intended purpose*. Both of these steps have been briefly discussed in this section, and will be elaborated in Chapter 4.

Finally, the team had to choose the format or language in which the team were going to build the architectures. The DoDAF offers two alternatives: (1) the Structured Approach and (2) UML. The team based the decision in convenience, practicality, and personal preference of the architects. In all three categories the Structured Approach came ahead of the UML. This was widely expected since UML is mainly used for software development although its use has increased in popularity in the recent years.

The structural model scope is presented in the next section. The assumptions made, the purpose of this model, and the design goals are analyzed. Finally the methodology used for the formulation of the problem is presented in detail.

3.7 Structural Model Scope of Work

Fatigue was a common failure mode of current aircraft structures. This was because the deterministic calculations of traditional fracture mechanics did not capture the probabilistic nature of material properties, manufacture and assembly, mission profiles flown, etc. This created a possibility of calculating a nonconservative fatigue crack growth at a FCL (Figure 3.12).

One way to mitigate the possibility of a nonconservative crack growth prediction was to conduct time consuming and expensive periodic inspections. The comparison of the baseline Cessna A-37 300 hour inspection schedule versus the extended inspection schedule with an ISHMS installed required the development of a structural model to predict the stress occurring at a FCL. The FCL chosen was the wing attach fitting at the wing root. The geometry of the fatigue crack growth was that of crack at an edge of a hole in tension from combined loading (Figure 3.13).

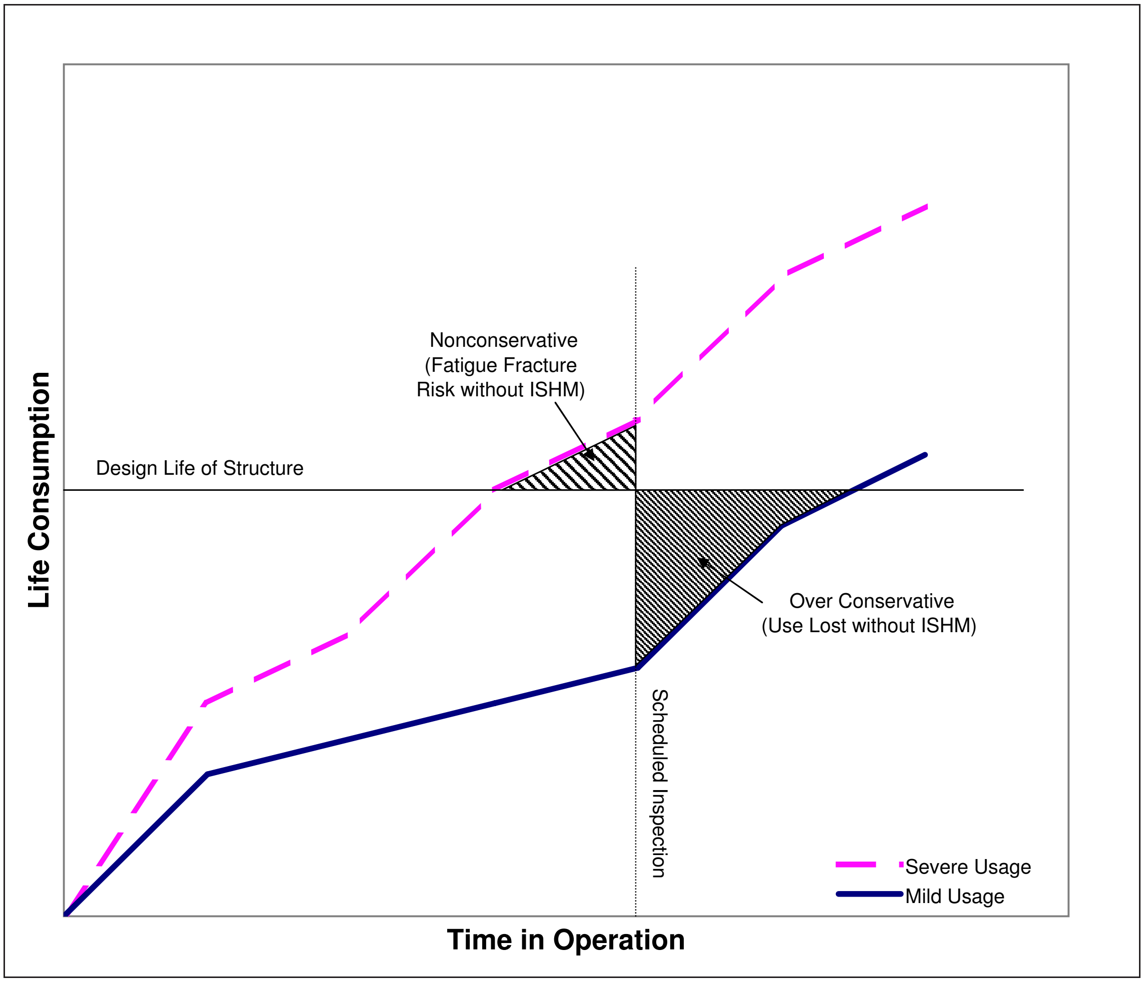

Figure 3.12: Effects of Deterministic Fatigue Crack Growth Prediction [49]

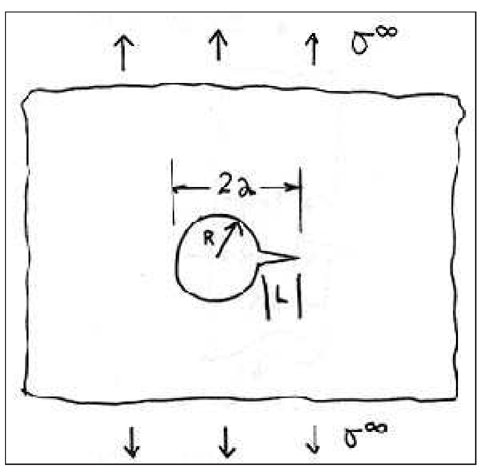

Figure 3.13: Wing Attach Fitting Crack Growth Geometry [28]

Additionally, the FCL was assumed to be in a state of plane stress(membrane). This required the additional assumptions:

1. Applied loads acted in the midplane direction and were symmetric with respect to the midplane
2. Support conditions were symmetric about midplane
3. In-plane stresses, strains, and displacements were uniform through the thickness
4. Normal and shear stress components in the z direction were negligible
5. Plate was symmetric with respect to the midplane
6. Material was homogeneous [31]

An established aircraft usage profile (flight spectrum) was used along with a typical Vietnam era weapons loadout of 2501 lb to estimate crack growth and determine aircraft service life (how many cycles the wings can be loaded until fracture). Countries can save maintenance resources by maximizing the inspection interval of the aircraft currently in their inventory while maintaining safety at the same level as the 300 hour inspection interval. Flight profiles and the amount of weapons carried cannot be modified without negatively affecting the mission, so the stress model at the FCL was determined with the pylon weapon loads as the design variables. Each weapon pylon location has maximum load ratings, but this structural model determines the stress applied at a FCL from the applied weapons load and flight profile.

This analysis modeled (via I-DEAS® Finite Element Analysis), metamodeled (via JUMP® response surface), and established a simple flight spectrum (via Excel® stepped approximation) the stress in the subsonic Cessna A-37 Dragonfly wing structure.

3.7.1 Introduction. The purpose of this structural modeling was to estimate crack growth propagation at a FCL to facilitate an ISHMS benefit analysis.

Due to the high cost of procuring new aircraft, many countries have extended their current aircraft inventory service lives beyond the original service life. Service life was determined by the calculation of cycles until failure, N_f (Equation 3.1).

$$N_f = \int_{a_i}^{a_f} \frac{1}{C\left(\Delta K\right)^m} da \tag{3.1}$$

The cycles until failure, N_f, was calculated based upon the crack growth rate, da/dN (Equation 3.2).

$$\frac{da}{dN} = C\left(\Delta K\right)^m \tag{3.2}$$

The Walker crack growth equation was used (Equation 3.3).

$$\frac{da}{dN} = C\left(\frac{\Delta K}{(1-R)^{1-m}}\right)^n \tag{3.3}$$

The crack growth rate, da/dN, was highly sensitive to the stress intensity range, ΔK, (Equation 3.4) and material constants, C & m.

The material constants were determined from the NASGRO database (Figure 3.14).

$$\Delta K = K_{max} - K_{min} = f(g) \cdot \Delta\sigma\sqrt{\pi a} \tag{3.4}$$

The stress intensity range, ΔK, was based on the stress amplitude, $\Delta\sigma$, the boundary condition factor, $f(g)$, and the crack length, a. The stress amplitude, $\Delta\sigma$, was the difference between the maximum and minimum stress (Figure 3.15).

Minimum stress, σ_{min}, was assumed as the unloaded wing configuration i.e., $\sigma_{min} = 0$. The aircraft flight load was assumed as Straight and Level Unaccelerated Flight (SLUF). The goal was to predict the maximum stress, σ_{max}, from the SLUF and weapon loading configurations. The difference in the two stresses was the stress

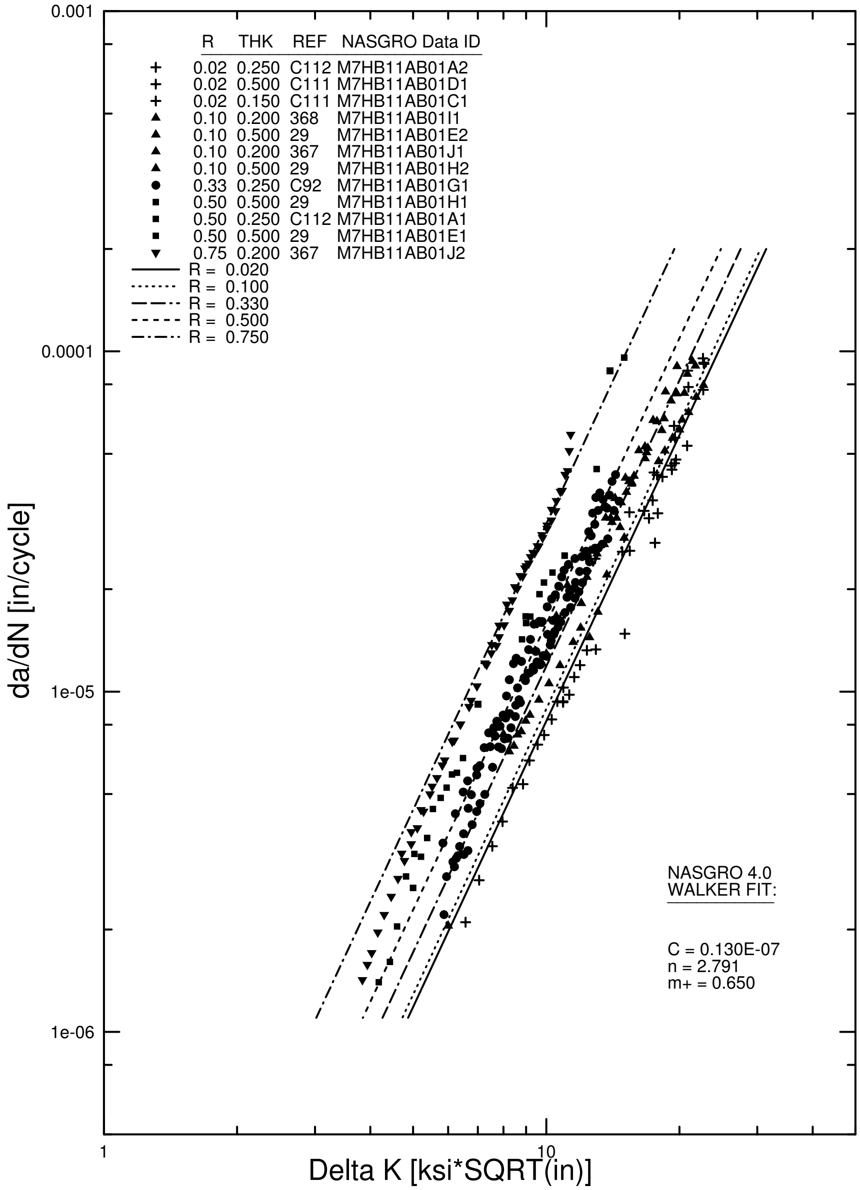

Figure 3.14: NASGRO Al 7075-T6 [30]

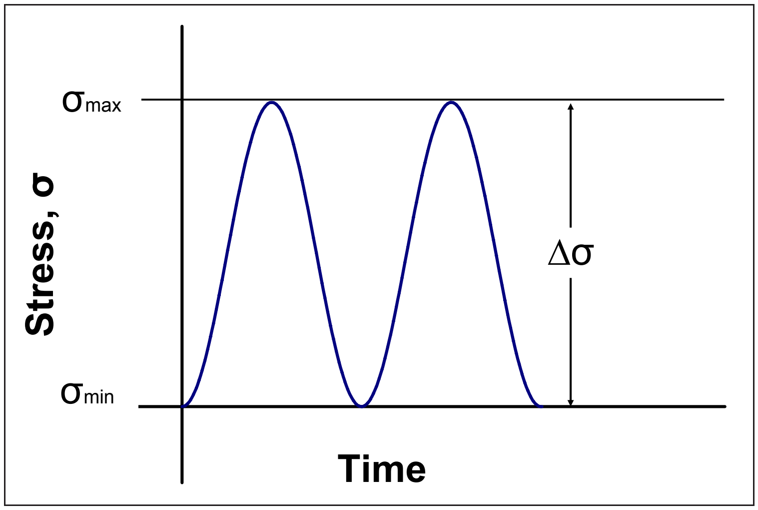

Figure 3.15: Stress Amplitude [28]

amplitude used to calculate the crack growth rate and cycles until failure, N_f. The maximum stress, σ_{max}, on the wing was determined by the weight/location of the weapons and the lift load.

The weapons point load stress was a function of gravitational force of the weapons and distance from the wing root (Equation 3.5). The lift distributed load magnitude was equivalent to the aircraft weight (SLUF assumption) and distributed in an elliptical manner from wing tip to root and elliptically from leading edge to trailing edge.

$$\sigma = \frac{M \cdot y}{I} = \frac{F \cdot x}{I} \cdot y \tag{3.5}$$

There was considerable research done in the areas low cycle fatigue, design of experiments, (and to a lesser extent) simulation with finite elements, and regression response surface metamodeling. Literature covering these modeling topics was listed in this section. Dowling exhaustively examined the factors influencing low cycle fatigue under constant amplitude stress [28]. Experimental design to minimize the number of simulations was well known, and Central Composite Designs were available from Draper [64] and demonstrated by Penmetsa [55]. Shih methodically presented the use

of the I-DEAS® finite element program to create structural simulation models [63]. Madu and Barton offered methodology useful to fit regression response surface metamodels to simulations [46]. Finally, Miedlar described the procedure to estimate an aircraft stress sequence [47].

3.8 Design Goals

The design variables were defined as the amount of weapon and fuel force (lbf) loaded at each of the four pylon locations and wing tip (x_1, x_2, x_3, x_4, & x_5) (Figure 3.16). Note: the location of the weapon pylons were fixed and could not be changed; only the amount of loading at each pylon location was changed.

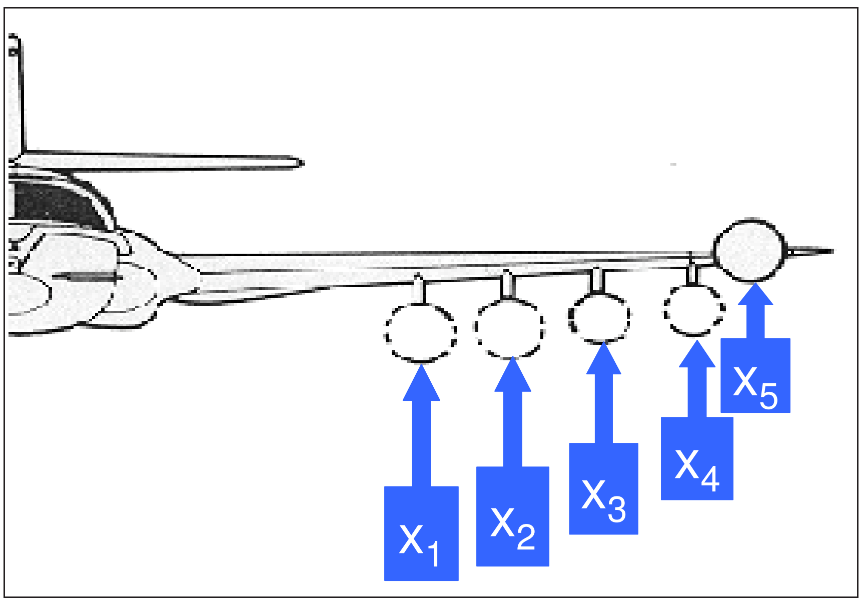

Figure 3.16: Design Variable Definition and Location [67]

The cost function was the aircraft stress (psi) at the wing root spar connection to the front spar carry-through frame (wing attach fitting) element 2815 (Figure 3.17).

3.9 Problem Formulation

Once a typical A-37 weapon load was determined, the development of the cost function was broken down into six stages and four parts. The first stage consisted of

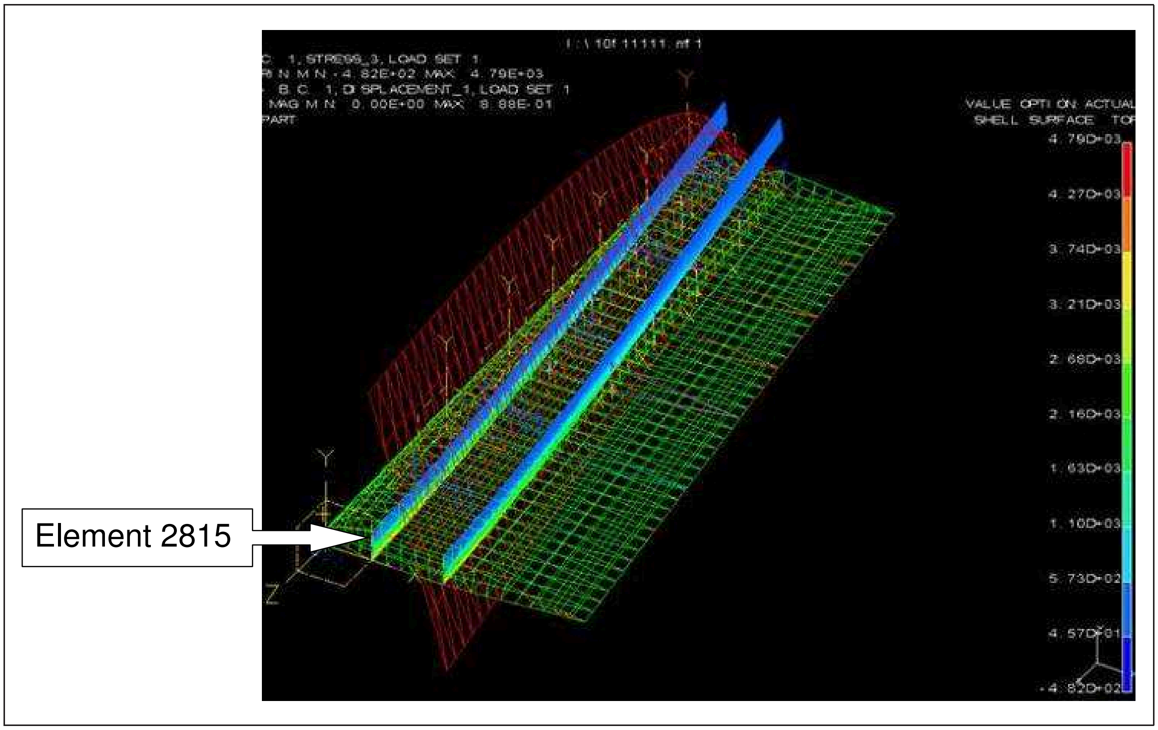

Figure 3.17: Spar Element 2815 Location

researching the Cessna A-37 Dragonfly to gain an understanding of the structure and forces at work. The second stage was making engineering assumptions to simplify the complex A-37 system into a structural simulation model. The third stage was distilling the simulation model down into a response surface regression metamodel to estimate the stress experienced at the wing attach fitting. The forth stage created a stepped approximation of a fighter flight spectrum to determine mission effects on the stress at the wing attach fitting. The fifth stage was feeding the stress amplitude per 100 cycles per flight hour into the MATLAB® crack growth model to estimate crack growth at the FCL over time. The sixth stage was using the crack growth model to conduct a benefit analysis (Figure 3.7).

3.9.1 Four Parts of Structural Model. The four parts to successfully execute the structural model were:

1. Constructed a structural simulation model of the Cessna A-37 Dragonfly
    - Created a simulation model of the wing using Finite Element (FE) analysis
    - Used adaptive meshing to decrease element size until max stress converged
2. Constructed a Central Composite Design (CCD) for the response surface
    - Generated orthogonal fractional factorial design to minimize confounding
    - Determined design factor input ranges
3. Executed each of the I-DEAS® finite element simulation runs
    - Executed required simulations from the fractional factorial design
    - Validated the simulation model results using hand calculations
4. Created a response surface regression metamodel of the FE simulation model
    - Conducted sensitivity analysis to determine loading trends on stress
    - Estimated stress at wing attach fitting using typical Vietnam weapon load-out
5. Constructed stepped approximation of fighter flight spectrum
    - Simplified flight spectrum for crack growth model
    - Estimated mission effect on wing attach fitting stress per flight hour cycle

In the final section of this chapter the ISHMS benefit analysis is discussed. The assumptions the thesis group made are presented. Also, the methodology used to conduct the benefit analysis, using a baseline and a scenario with the ISHMS installed, is explained.

3.10 ISHMS Benefit Analysis

Utilizing the FCL material analysis and crack growth models discussed previously, this thesis performed a basic analysis to help verify and possibly quantify the potential cost and safety benefits of an ISHMS over the current baseline which is to continue to fly aging aircraft with the increased inspection profile. Monte Carlo simulations were generated using MATLAB® to contrast the failure rate of a FCL and number of inspections performed under two scenarios:

1. baseline - continue to fly with mandatory 300-hour inspections
2. to fly with the same 300-hour inspection interval but the additional protection of an installed ISHMS.

The only difference between the two scenarios was the ISHMS monitors the FCL in real-time and if the crack grows to 90% of critical length, the ISHMS provided warning to either the cockpit or the ground that the aircraft must land and be inspected. This design assumption helped to simplify the simulation model. Figure 3.18 provides a graphical depiction of the perform simulation function.

3.10.1 Simulation Assumptions. Some simplifying assumptions were made in order to accurately compare the two scenarios. The simulations assumed only one crack growing in one FCL. The effects of corrosion were not included in the model. Crack propagation was the only contributing factor to FCL failure. When cracks are discovered through maintenance inspection, they are repaired and the new crack length is assumed to be the longest length undetectable to the human eye. This simulated the worst case of maintenance personnel installing a new part with a material flaw, but, of course, that flaw is not seen by the maintenance personnel. The maintenance inspections performed for both scenarios are identical. The ISHMS can monitor the entire FCL for any size crack initiated in any location on the FCL and growing in any direction. Both simulations assumed the same beginning crack length and the crack growth was identical for each simulation. Each simulation simulated a

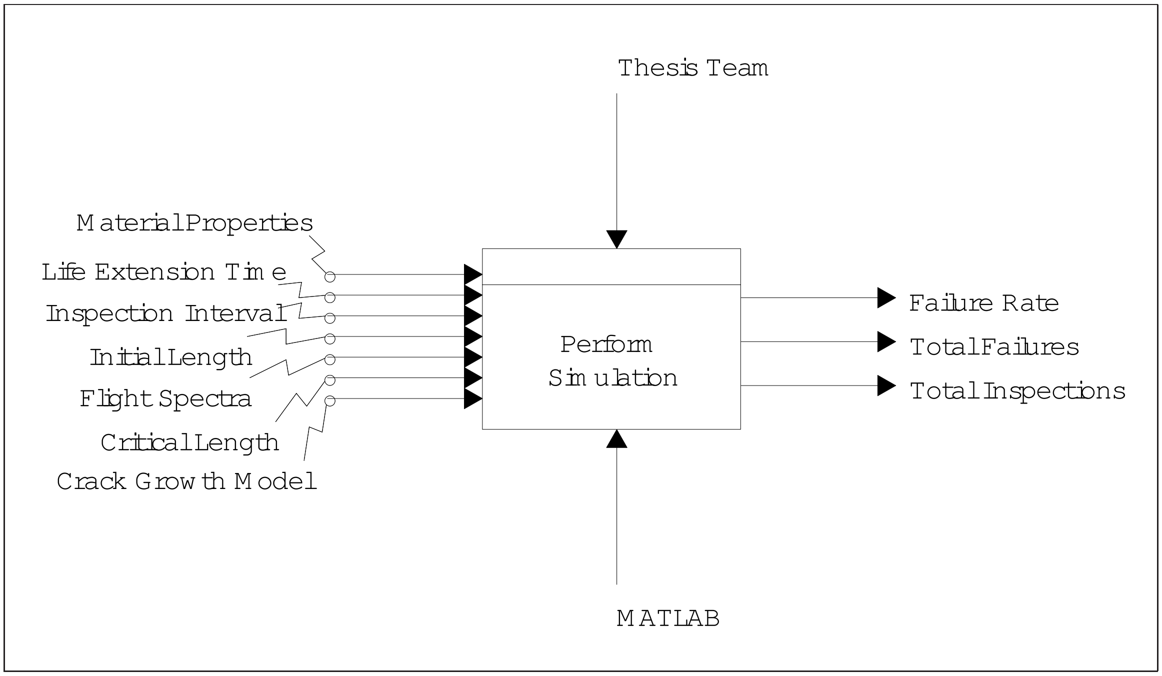

Figure 3.18: Perform Simulation Function

fleet of 13 A-37s through 1000 trials with a life of 5000 flight hours for each aircraft. One thousand trials were chosen to maximize the number of trials while keeping run times reasonable. The team selected 5000 additional flight hours as an appropriate life extension timeframe for an A-37 aircraft.

3.10.2 Baseline Scenario. In the baseline scenario, the FCL began with one crack set to the initial length predetermined from the material analysis performed on the FCL. The crack grew according to the growth model and at intervals of 300 flight hours the aircraft was inspected. A probability of the maintenance inspection detecting the crack was applied to the simulation. The thesis team estimated that maintenance inspection would detect 97% of cracks. This probability was based on the experience of the maintenance officer group members. Additionally, any error in this estimate would be mostly negated because both simulations used the same probability estimate. If the crack was detected, repair was accomplished that effectively removed the crack and the crack length was reset to the longest crack length undetectable by human sight. A critical crack length was defined from the material analysis performed

in the previous sections. If the crack length ever exceeded the critical crack length, due to lack of detection during inspection or growth prior to inspection, then failure of the fatigue critical location and, subsequently, aircraft failure was considered a result. As stated 1000 trials of the simulation were run simulating a fleet of 13 aircraft for each trial. The resulting failure rate per million flight hours and total number of inspections were calculated.

3.10.3 ISHMS Installed Scenario. As in the baseline scenario, the fatigue critical location began with one crack at the initial length and crack growth was modeled. A design assumption for the ISHMS had to be made. It was assumed that the ISHMS provides near-real-time feedback to the either the aircraft pilot or ground control on the status of the monitored structures. The ISHMS signaled when the crack length had reached 90% of critical length. For the simulation, the aircraft will undergo inspection either at a given flight hour interval or whenever the ISHMS indicates 90% critical length. If the ISHMS indicated a crack had grown to 90% of critical length causing an unscheduled inspection, then the inspection interval clock was reset and the next inspection occurred after the requisite flight hours. There was a probability of detection associated with the ISHMS detecting the crack (99.9%) and a separate probability of detection with the inspection detecting the crack, if not tipped off by the ISHMS (same as baseline - 97%). These probabilities were considered by the model. However, if the ISHMS indicates a crack near critical length, the probability of detection by maintenance inspection was 100%. As in the baseline scenario, if the crack length exceeded the critical crack length, due to lack of detection by ISHMS and/or inspection, then aircraft failure resulted. Again 1000 trials were run simulating a fleet of 13 aircraft for each trial. The resulting failure rate per million flight hours tested and total number of inspections were calculated.

3.10.4 Sensitivity Analysis. The probability of detection for both the maintenance inspection and the ISHMS were selected rather arbitrarily. To examine what, if any, changes in the results might occur if the probabilities of detection were differ-

ent, a sensitivity analysis was performed on the maintenance probability of inspection. If the probability of detection for maintenance were decreased, the safety benefit of an ISHMS would certainly increase; therefore, the sensitivity analysis only examined the effect of increasing the maintenance probability of inspection. The sensitivity analysis did not vary the ISHMS probability of detection, because the thesis team believed that 99.9% probability of detection would most likely be the minimum acceptable probability of an ISHMS by a user.

IV. Results

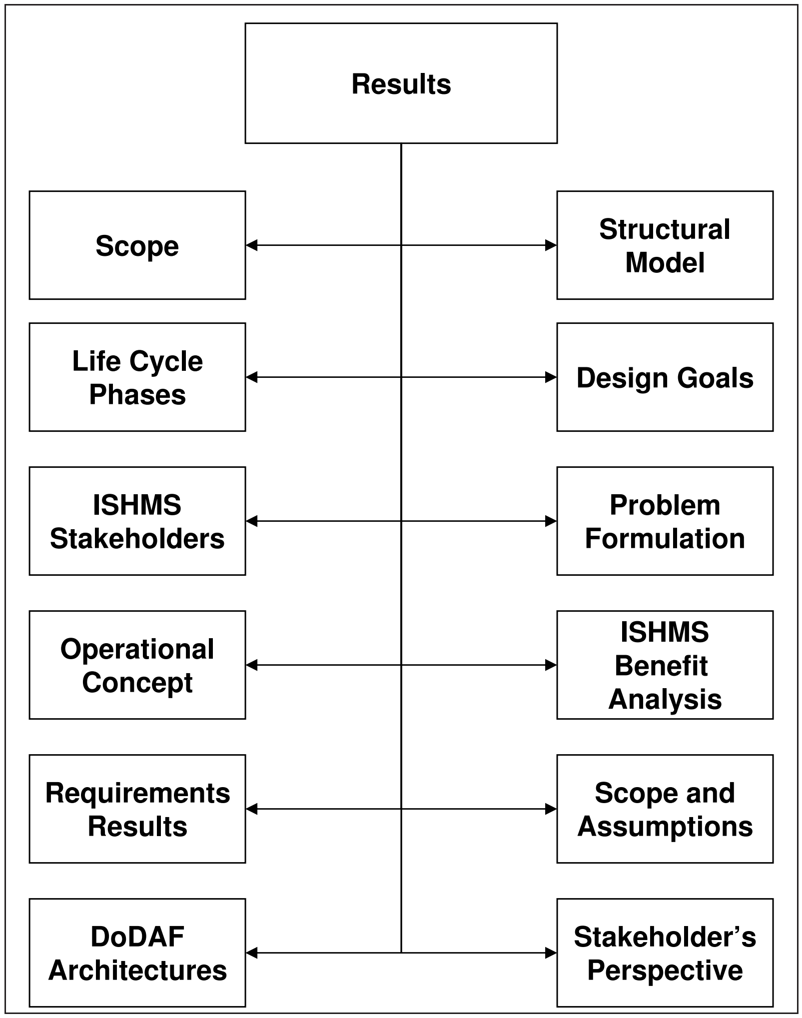

Figure 4.1: Chapter 4 Decomposition

The results of implementing the methodology detailed in Chapter 3 are presented here. The systems engineering products which help to define the system are shown. The aircraft wing attach fitting material analysis and modeling is detailed. The chapter concludes with the output of the benefit analysis comparative simulation runs to quantify the potential cost avoidance provided by installing an ISHMS on aging aircraft. (Figure 4.1)

4.1 Scope

The ISHMS thesis team considered many different aspects of the problem to adequately scope this thesis. Scoping the thesis resulted in two basic deliverables. The first product was the ISHMS SE design process. The second product was the benefit analysis of installing an ISHMS.

4.1.1 ISHMS SE Design Process.

The ISHMS SE design process involved a significant challenge in defining the problem and determining the problem statement. After several iterations, the problem statement converged to *develop a systems engineering approach for a near real time, cost-effective, integrated structural health monitoring system for an aging aircraft while maintaining or improving the safety of flight parameters*. The original scope was to execute the SE process through development of the ISHMS physical architecture. However, limitations of time, funding, sponsorship, and test aircraft availability determined the scope of the SE design process to the functional architecture. Therefore, this thesis focused on developing a systems engineering approach to developing the functional architecture.

Each aspect of the problem statement was defined.

1. Near real time
2. Cost-effective
3. Integrated structural health monitoring system
4. Safety of flight

4.1.1.1 Near Real Time.

Defining *near real time* was broken into two parts. The first part was determining the sampling rate of the sensors at the FCLs. The second part was determining the communication interval of the ISHMS system to the aircraft operator and aircraft maintenance technicians.

The sampling rate of the sensors of the ISHMS was estimated by dynamically modeling the first bending natural frequency mode of a Cessna A-37 wing using

an I-DEAS® finite element structural model. This modal frequency was used to determine the Nyquist sampling rate of the sensors. The Inquest sampling rate was the minimum sampling rate of the ISHMS sensors at the FCLs to capture the cyclic vibration loading.

The communication interval of the ISHMS system was determined differently for the operators and maintainers. The aircraft operator was notified by the ISHMS when crack length sensors estimated only 10% of the fatigue life was remaining. This impending failure pilot notification allowed a reasonable amount of time to land the aircraft for inspection and repair. The communication interval for the maintenance personnel was based upon the extended maintenance interval for the installed ISHMS (approximately every 600 flight hours).

4.1.1.2 Cost-effective. Defining *cost-effective* for this thesis was very difficult. The total life-cycle cost of the ISHMS must be less than the cost of continuing the current course of action of inspecting at a predetermined amount of flight hours flown (i.e. 300-hour inspection interval). The ISHMS life-cycle costs include every cost from *cradle-to-grave*:

1. Cost of design
2. Cost of acquisition
3. Cost to install the ISHMS
4. Additional Cost of disposal
5. Cost of transmitting the data (if commercial satellites used)
6. Training to use equipment
7. Cost to maintain the ISHMS

Unfortunately, costs for the baseline 300 hour structural inspections, as well as, the additional cost of installing the ISHMS sensors and components were not available.

Cost-effective was defined by the cost avoidance of utilizing the ISHMS versus the baseline 300 hour inspection scenario. The ISHMS was determined *cost-effective* if there was an estimated cost avoidance from utilizing the ISHMS versus the current 300 hour inspection intervals.

4.1.1.3 Integrated. Defining *integrated* for the ISHMS was much easier than determining the level of integration required. Ideally, the ISHMS was integrated among the FCL sensors and throughout the aircraft subsystems. However, the expense of a new ISHMS subsystem integration into existing legacy aircraft subsystems (e.g. power, avionics, etc.) was considered cost prohibitive. The ISHMS different types of sensors (i.e. strain gauges, peizo-electric, etc.) were integrated to monitor fatigue and crack growth. The ISHMS was assumed to detect all types of fatigue/cracks growing in any direction at all lengths for all of the critical locations that were being monitored. All the FCL sensors must be integrated to provide a high level of accuracy and reliability.

The advantages of installing an ISHMS were weighed against the increased costs. The ISHMS thesis group decided to minimize ISHMS integration with the existing legacy aircraft subsystems to avoid increased design, installation, and testing costs. The ISHMS was defined as integrated if the ISHMS had the ability to collect and synthesize the various FCL sensor data and provide structural health cuing to the pilot while storing the data for maintenance retrieval.

4.1.1.4 Safety of Flight. *Safety of Flight* was defined as the USAF standard of 10^{-7} probability of fracture per flight hour [65]. The acceptable level of risk was one loss per 1000 aircraft over the life of the weapon system.

4.1.2 Benefit Analysis. Previous attempts to quantify the benefit of installing an ISHMS on legacy aircraft were not found during the team's review of relevant literature on the subject. The primary purpose of installing an ISHMS was reducing the operating cost of flying legacy aircraft. The ISHMS team decided that

estimating the cost avoidance and safety benefit of installing an ISHMS was an important deliverable adding to the current body of knowledge. The ISHMS team used the Cessna A-37 as the benefit analysis example aircraft. A finite element wing structural model was constructed and a static stress analysis was conducted to determine an FCL location at the front spar wing attach point. This FCL was chosen for the analysis because of the high stress at the front wing spar attach point. The FCL location was verified with current A-37 maintenance data as a fatigue crack growth location. The wing attach fitting geometry and structural simulation model were used to predict stress at the FCL location for level flight. A-37 mission profile data was not available, so a general fighter aircraft stress sequence was used to determine the stress effect per flight hour cycle. The results were inserted in the Walker crack growth equation. Two MATLAB® crack growth and detection simulations were performed to gain a rudimentary analysis of the benefit of an installed ISHMS with respect to both safety and cost. Maintenance interval was incrementally increased on the ISHMS to determine cost avoidance possible on an ISHMS aircraft at an equivalent level of safety to the baseline 300 hour inspection aircraft.

The SE process and benefit analysis were discussed in following sections of the thesis. By focusing the scope to a Cessna A-37 example, the amount of assumptions made actually increased. The ISHMS team realized that the definition of the physical architecture by follow-on thesis groups will improve the fidelity of utilizing an SE process for the design of an ISHMS.

The results of the SE process life-cycle phases are presented in the following section. Analogous to the life cycle phases of an aircraft, the SE process is grouped into periods that allow the methodical discovery and refinement of the ISHMS requirements.

4.2 Life-cycle Phases

The term *life-cycle* is used to represent a series of stages through which a system passes from its inception to its retirement. Life-cycle is also characterized as "birth

to death” [17]. The life of any system begins with the emergence of a *need* for the users. The next step is the definition of this *need* and of the system requirements, so that the stakeholders’ expectations from the system are reflected in the design. This step is the beginning of the development period where the systems engineers and the stakeholders are working together. Following the completion of the design phase is the integration phase, the production, the operational use, the refinement and finally the retirement, disposal or replacement phase [17]. During the design phase all these phases must be taken into consideration otherwise the design may end up being a failure.

These phases can be grouped into four periods. First is the development period, where the requirements, architecture and models are developed. Production, training and deployment take place during the second period. During the third period the operational use of the system takes place along with the maintenance and (if needed) the refinements/improvements. Retirement, disposal and replacement take place at the end of the life-cycle and consist the fourth period.

Figure 4.2 shows one way to depict the life-cycle phases and the periods described above.

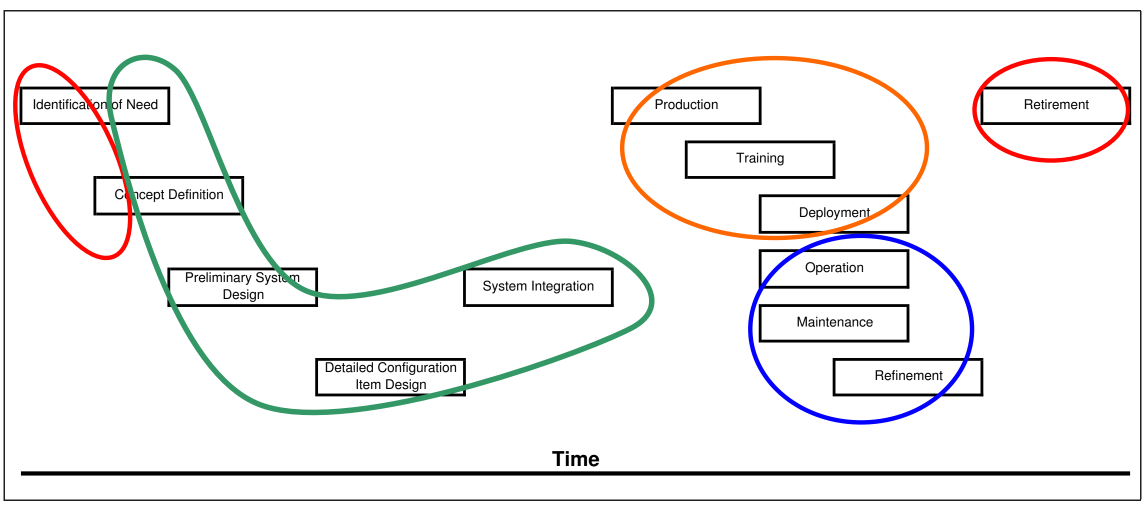

Figure 4.2: Life-cycle Phases

The thesis team can see that there is a fifth period, which is shown on the left side of the figure. This period is not clearly part of the life-cycle of the system since the design has not started and the system does not exist yet. However, it is during this time that the need for the system emerges (usually imposed by a problem that needs to be solved or a situation that must be improved) and the system concept (a high level definition of the system's function) starts taking shape. Therefore, this period is depicted in the figure.

Although the life-cycle phases are shown as distinct and separate items in the figure, in fact they are not. Each phase is a continuation of the previous one. Also, this categorization of the life-cycle phases and their grouping into four periods is not a unique approach and it is not generally applicable to every system. Differences in the categorization of the life-cycle phases are very common among different products, customers and industries [20]. However, for the purpose of this thesis, this is the categorization of the life-cycle phases that will be used for the ISHMS.

4.3 ISHMS Stakeholders

The thesis team mentioned in the methodology that it created a list of the ISHMS life-cycle phases and tried to identify the stakeholders for each phase. Then, by playing the role of the stakeholders, the thesis team tried to understand and describe the viewpoint and the requirements of each category of stakeholders.

In order to identify the stakeholders, a critical question the thesis team had to answer was *"who has the right to have a requirement for the system?"* [17]

For the first phase, *identification of need*, the thesis team identified the Coalition Force's Ministry of National Defense, and the Coalition Air Force as the main stakeholders. Both these stakeholders are part of the country's government who is the *ultimate* stakeholder. The government, however is a more *conceptual* stakeholder (who needs to ensure the safety of the country and organize its defense) who does not pose requirements directly related to the system. Both these stakeholders can be

further broken down (based on their organizational structure and the hierarchy) into smaller groups of people who have a need for the ISHMS.

The stakeholders on the Ministry of Defense side are the *Joint Operations Planning* agencies. They need to ensure enough air strike capabilities are available in order to accomplish the defense operational plans. Since the A-37 aircraft are undergoing long inspections, are not mission available and are also close to the end of their design life, these stakeholders have the problem that they cannot achieve their capabilities goals. Usually, the Ministry of Defense is controlling the defense budget so the *Finance* and *Acquisition* agencies can be considered as the bill payers and subsequently as stakeholders.

At this point, the thesis team should note that for the analysis in this thesis *a basic assumption* was the two main stakeholders, Ministry of Defense and the CAF, have already conducted an analysis for the problem they are facing and have identified the ISHMS as the most beneficial solution. Therefore, further analysis is centered on this solution only.

The CAF has a number of airplanes and weapons in its inventory and trained personnel to operate, maintain, and support those airplanes in order to be able to satisfy the Ministry of Defense requirements. Also, it has a budget that limits its ability to maintain and/or increase this force. The CAF has a limited level of support capabilities (facilities, equipment, personnel) that put restrictions on the amount of maintenance it can be performed. As the thesis team discussed the problem for the CAF arises from the fact that some of their A-37 aircraft are approaching their design life limit and are either unavailable due to extensive maintenance or about to be retired (thus reducing the total amount of operational capabilities). This situation consumes a larger than the normal amount of the CAF's financial resources and consumes additional support capabilities thus creating more problems.

On the CAF's side, the thesis team can distinguish four groups of people/agencies that are affected by this problem and are in need of a solution: *Operations, Maintenance, Logistics/Acquisitions, Flight Safety*.

The operations agencies can be broken down into:

- Headquarters Operations (HQ) agencies (whose purpose is Mission Planning)
- Base Level Operations (who are involved with pilot training and mission execution)
- Squadron Level Operations (namely the pilots)

The HQ Operations agencies are responsible for maintaining a certain level of air-power readiness in order to be able to execute the defense plans assigned to the CAF by the Ministry of Defense, their *customers*. These agencies set the acceptable aircraft availability limits the Base Level Operations must maintain. Base Level Operations must, also, maintain a certain level of training and expertise for their pilots and be able to execute the missions assigned. The Squadron Level Operations needs to execute the training program and maintain their readiness at the level their customers (Base Level Operations) require.

The situation created by the aging of the A-37 aircraft (reduced availability, possible restrictions in the operational use of the aircraft, reduced number of aircraft due to life exhaustion, etc) prevents all these agencies from accomplishing their goals. Therefore, these agencies need a solution that will permit them to achieve the availability and accomplish the training requirements.

From the viewpoint of this category of stakeholders (especially the pilots), the health monitoring system should relieve the current restrictions in the operational use of the aircraft (e.g., configuration, flight envelope restrictions) and they do not want new restrictions imposed because of the system.

The people involved with aircraft maintenance that can impose requirements on the system can be categorized as follows:

- CAF engineers
- Maintainers at the CAF HQ
- Maintainers at the Base Level
- Maintainers at the Squadron level

The CAF engineers must deal with the aging A-37 problem. They need to decide whether to retire the aircraft that reach their design life or extend their operational use. If they decide the latter, they need to decide how this will be accomplished and how long this extension will be. From their viewpoint an ISHMS that records and analyzes aircraft usage data will allow them to assess the aircraft condition, predict the remaining useful life and make decisions on the aircraft life extension and maintenance. They expect that this system will permit the development of a customized maintenance schedule which will have as a result the increase of the aircraft availability. At the same time, they expect high reliability from the system that will be a valuable tool for achieving their goals.

The maintainers at the HQ need to find a solution to the problem created by the A-37 aircraft. There is increased downtime and reduced number of operational aircraft due to the extensive inspections and repairs. Also, these inspections consume more resources (facilities, equipment, personnel) than expected, and hinder the maintainers at the Base and Squadron Levels from satisfying their customers' (Operations) requirements: provide mission ready aircraft on time. The maintainers expect a system that will be able to track the actual usage of the A-37 and monitor the structural damages. They expect that, if they have this information they will be able to inspect and repair only the problem areas on the aircraft that must be inspected/repaired. This will reduce the amount of teardown and the maintenance effort overall. Also, they want to be able to perform inspections when it is required and not according to a preset schedule which may not reflect the true condition of the aircraft. At the

Base and Squadron levels this will allow better use of the resources (especially the personnel).

Another *assumption* that the thesis team made was that the CAF does not have an aircraft depot facility and any depot maintenance required is accomplished at a commercial aircraft depot either in the same or in another country.

Because many of these structural inspections are being conducted at a depot facility the CAF has to pay for this maintenance. The maintainers at the HQ believe that the installation of a health monitoring system will reduce this portion of the maintenance costs.

The Logistics agencies are coping with problems in the support of these aged aircraft. Currently, they have a hard time getting the required structural parts in a timely manner when a repair is needed. They found out that by ordering parts based on the preset maintenance schedule of the structural inspections, they end up paying for and receiving parts that are not truly required on every aircraft (which means wasted resources). The reason is that the preset schedule assumes that some parts will be defective and will require replacement. However, when some aircraft are inspected they may not exhibit the expected findings and there may not be a need for replacement parts. On the other hand, parts required for a specific aircraft based on its condition may not be immediately available because there was no prediction for this requirement, and that increases the aircraft downtime. They perceive the ISHMS as a system that will allow for better predictions in the maintenance requirements and will result in more accurate parts order and less waste.

The CAF Acquisition agencies have a problem because the A-37 aircraft inspections consume an increased portion of the budget due to higher maintenance costs. They have already done their analysis and expect the acquisition of this new system will help better control the A-37 fleet's direct operating costs. They have their estimates for the ISHMS costs and expect a physical realization of the system to meet these estimates.

Flight Safety agencies are probably the stakeholders with the strictest demands. They are in charge of setting the acceptable safety limits and ensuring the limits are being followed. They have a hard time with the A-37 fleet: the increased age is translated into increased risk. They want to be sure that if an A-37 is allowed to continue flying (especially beyond its original design life) this is done without any compromise or any violation of the required safety level. They expect from an ISHMS to maintain at least the same level of safety as the current solution of performing the structural inspections. All these stakeholders, for the first phase of the life-cycle, are shown in Figure 4.3.

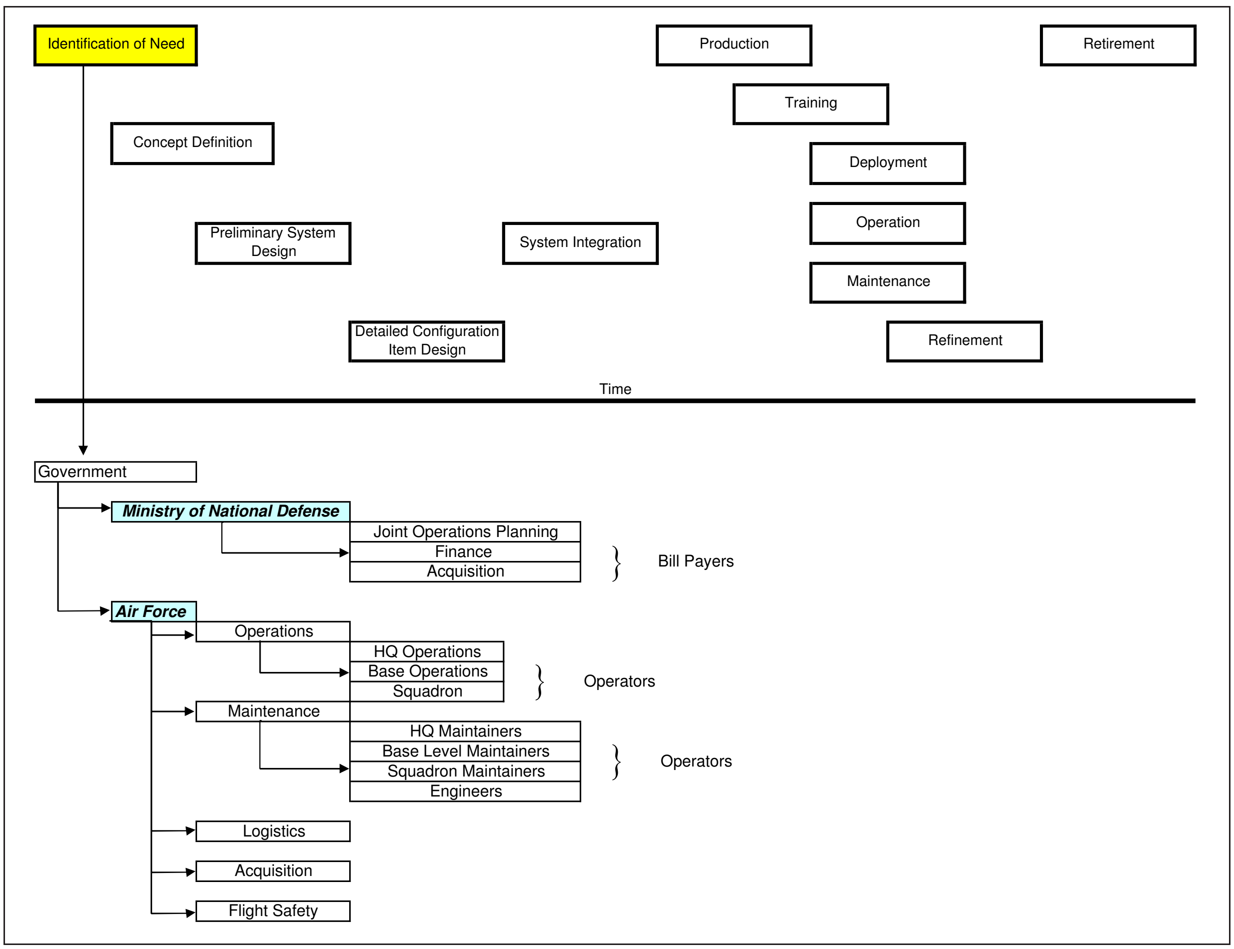

Figure 4.3: Stakeholders Identification of Need

The second phase of *concept definition* cannot be separated from the first. There is not any major change in the stakeholders but now the systems engineers (develop-

ers) are required to work with the representatives of the stakeholders detailed above and transform their generic needs into an operational concept. They also need to identify the subsequent phases and the stakeholders involved in these phases.

In the following phases (preliminary system design, configuration item design, system integration), which consist the development period, the main stakeholders are the systems engineers (developers) and the system designers. The manufacturers have also a role while the regulatory agencies and the U.S. Department of Defense (DoD) may impose requirements. The stakeholders for the development phase of the system are depicted in Figure 4.4.

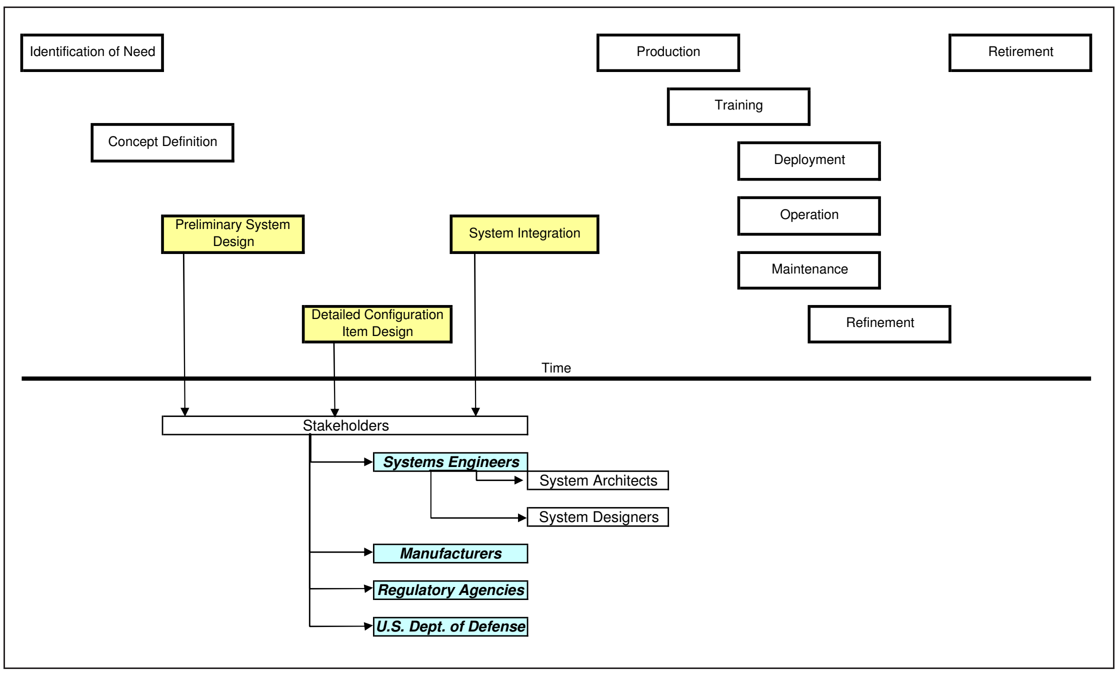

Figure 4.4: Development Phase Stakeholders

The developers at this phase want to define the system requirements based on the concept definition they created previously. They also want to define the architecture of the system and make sure it reflects the other stakeholders' views. At the same time they must pay attention in treating the system as a *black box* (which is quite difficult to do). This means they should not direct the designers towards a specific realization of the system at this time but instead, they should keep their focus on

the functions of the system. They are responsible for envisioning the evolution of the system through its life-cycle. The schedule constraints, the availability of funding, the operational requirements, the system's performance and the technology applied should be balanced by these stakeholders.

The designers are another group of stakeholders since they are involved with the transformation of the requirements and architectures into a physical solution. Their vision of the system may be different than the vision the other stakeholders may have. But the designers must keep in mind that it is the customers' needs they are trying to satisfy with the design and not their personal visions or goals. In this sense the technologies they are going to use for the design should not be selected on the basis of "technology for the technology's sake" [1].

The manufacturers start getting involved during these phases. They expect that the system design they will have to materialize will be feasible. This means that the technology involved and the resources required will be within their capabilities. Also, their financial goals (from the manufacturing of this system) will create some requirements for the system design. Clear definition of the requirements is expected in order to avoid misunderstandings later on. The manufacturers view this phase as the preparation stage for their more extended involvement later on.

By the term *regulatory environment* the thesis team refer to all those agencies that can impose requirements and rules that affect the design, production and operation of the system. These agencies usually are external to the system's environment. Rules regarding the use of hazardous material in manufacturing and operation and the production of toxic waste for example should be taken into account during the design. In this sense, the regulatory environment is another stakeholder at this phase.

During the design phases as well as in the subsequent phases (i.e. Production, Operation) the U.S. DoD is another significant stakeholder. The reason is that the CAF has coordinated the development of their A-37 ISHMS with the U.S. DoD. The DoD has the right to limit the amount and the types of technology that can be

released to other countries, and because the development of the ISHMS will be done by researchers in the United States, therefore the DoD can impose some requirements (restrictions) for the capabilities of the system.

In the production, phase the manufacturers (contractors) are the main stakeholders. Other stakeholders are the CAF engineers and acquisition officers, and, as the thesis team mentioned, the US DoD and the regulatory agencies.

A part of the manufacturers' view of the system at this phase was described earlier. Their main expectation is that the undertaking of producing the system will be beneficial for them. The system's production requirements should not create additional difficulties in their activities. Their investment for this production in additional equipment needed is expected to pay off. Along with setting up the production line, the manufacturers must consider during this phase the support they will provide to their customers (i.e. training, technical support). They should not forget, though, the regulatory agencies and their restrictions when organizing the production line in order to avoid any conflicts that might affect the timely production of the system.

A problem related with the production is the selection of suppliers. Very often this decision at this phase will affect the system's support in the subsequent phases and the manufacturer should take into consideration factors such as the life expectancy of the system, the technology involved, and the ability of the various suppliers to provide the parts needed in the long term.

The CAF Acquisition officers need to ensure at this phase that contractual obligations are being met by the manufacturer. The Air Force engineers are working with the manufacturer and are *monitoring* the production process to verify that the technical specifications are followed. Their feedback is expected by the acquisitions officers in order to verify that the production proceeds according to the schedule and the contract.

As the production of the first systems goes to its completion, the final preparations for the next two phases begin. Training as well as the system's deployment is

organized at this time. In the training phase, the two large categories of stakeholders are the trainers and the trainees. In the trainers category the manufacturer and the CAF training agencies are the main stakeholders. The category of trainees consists of the system operators, the system maintainers, and the aircraft operators (pilots). The manufacturer's technical personnel involved with the support of the system in subsequent phases, have also requirements for training.The groups of stakeholders during the training phase are depicted in Figure 4.5

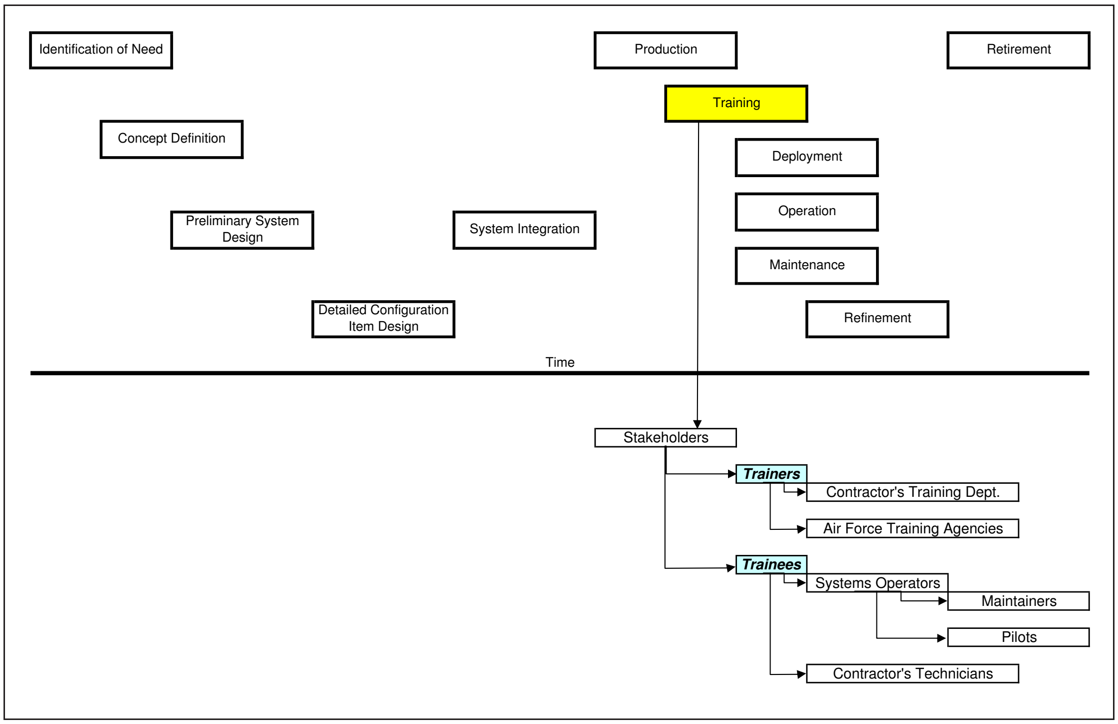

Figure 4.5: Training Phase Stakeholders

Usually, the manufacturers of systems complex and expensive such as the ISHMS have their own training personnel to provide training to their customers. These trainers produce the training material and organize the training requirements. Duration of training, location of training (manufacturer's facilities or customer's site), type of training (theoretical in class training, hand-on training, combination) and training aids are factors that must be considered by the trainers.

The CAF internal rules impose requirements on the form of training. The CAF training agencies need to ensure that the training provided by the manufacturers is according to their requirements. Most importantly they must ensure that the training goals are accomplished and the trained personnel are knowledgeable enough to operate and support the new system.

The trainees expect from the training to provide them with the necessary knowledge to support the system once it becomes operational. Each group of trainees (operators, maintainers, pilots) has different expectations from this training. That is translated into a requirement the development of training programs adapted to the needs of each group.

The deployment phase cannot be clearly separated from the production and training phases. Essentially, the completion of the first systems and the beginning of the personnel training initiate the deployment phase. During this phase the groups of people that *have the right to have requirements for the system* are the manufacturers, the groups within the CAF described earlier (i.e. Headquarters, Base, Squadron, Operations, Maintenance) as well as the developers. The stakeholders for this phase are shown in Figure 4.6.

At this phase, the manufacturers have completed production and, in coordination with the CAF organize the installation of the system on the aircraft. Details such as where the installation will take place, who will perform it, how integration testing will be done need to be clarified before the deployment begins. The manufacturers' expectation is that the system could be installed during another scheduled or unscheduled maintenance in order to reduce the installation time. They would like to be able to perform testing within a relatively short period of time and even combine this testing with other operational tests performed on the aircraft. They would like to minimize the potential problems that could arise during the installation. Their basic goal is to minimize their portion of the costs related to the system's deployment.

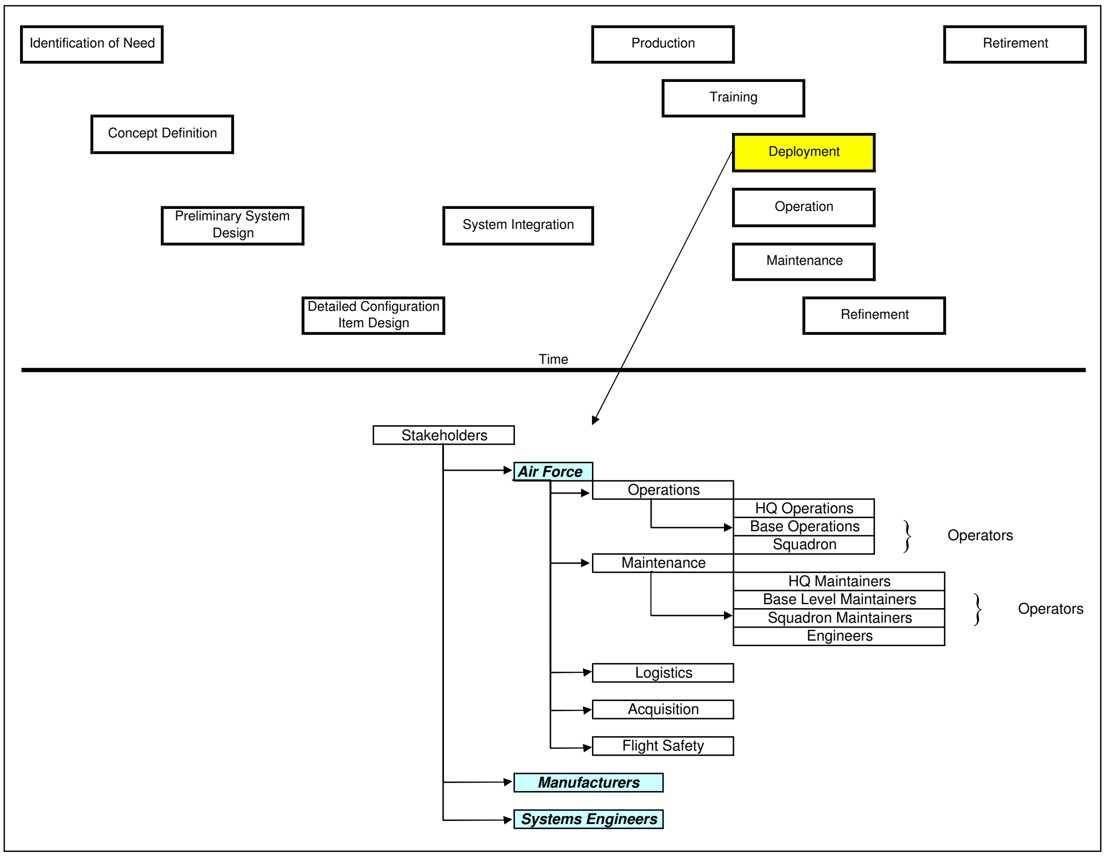

Figure 4.6: Deployment Phase Stakeholders

On the CAF's side decisions concerning the location, the personnel, and the support equipment required, should have been made at the beginning of this phase. Their participation in the installation of the system as well as the requirements for the acceptance of the new system must be clearly defined in order to avoid delays and conflicts with the manufacturers. Their main expectation is that the integration of the system on the aircraft will have minimum impact on the operational use of the aircraft.

The developers, on the other hand, are eager at this phase to see the results of their work. Their main expectation is that the design they produced and the planning they have done will permit the deployment of the system to be completed with the minimum impact to the other stakeholders (manufacturers, CAF agencies).

During the *operation phase* the stakeholders are the same as in the very first phase *identification of need*. As the thesis team discussed the reason for the design and production of the ISHMS for the CAF A-37 fleet was a problem that affected the stakeholders such as the country's Ministry of Defense, the CAF, and a number of agencies in these two organizations: the Operations agencies, the Maintenance organizations, the Flight Safety agencies, etc. All these categories of stakeholders were affected by the main problem in different ways, and therefore they had different expectations and visions for the system. The expectations and the vision of each stakeholder from the operation of the system have already been presented.

As the system becomes operational each category of stakeholders is evaluating to what degree this system satisfies their needs. This is essentially the phase where the stakeholders decide whether all the effort, the expenses, and the wait were worth it.

Hopefully, the stakeholders identified by the systems engineers in the initial phases was complete and everyone's vision was captured in the design. If this was true it is possible that the system will be accepted by the stakeholders. Otherwise some of them may view it negatively.

The operational phase occurs simultaneously with the maintenance phase. The maintainers are the main stakeholders in this phase. These are the Base and Squadron level maintainers but the technicians involved with the repair of the system at the manufacturer's depot facilities can also be considered stakeholders.

The CAF maintainers' vision of the system at this phase is that it is a highly reliable system which performs all the functions they initially requested. They would like the system to be easy to maintain (i.e. to experience a low number of failures, to require small amount of teardown to gain access for repair, and to require a small amount of downtime). Self-diagnostics capabilities of the system are viewed as a highly desirable feature.

The manufacturer's technical personnel have similar expectations from the ISHMS. They would like the system to experience few serious failures that require their intervention. In case some of the system's components are sent to them for repair, they would expect that the necessary testing and repair equipment is available and the repairs feasible.

As the system stays longer in operation, the need for some improvements or upgrades may arise. This need may be created by the feedback provided to the developers and manufacturers from the operators. These groups are the main stakeholders in this phase.

The developers envision a system that will operate smoothly throughout its design life. However, after the system has been deployed and put into operation there might be problems they did not anticipate. In order to be able to deal with these problems, the developers would like to receive frequent and accurate feedback from the operators. Therefore, they would like to have a communications scheme to permit this information to flow back and forth from the field back to them. Also, they envision the ISHMS as a system that can perform self-diagnosis and provide accurate data about its condition. Thus the feedback from the field can be *automated* and independent of the maintainers. The improvements during this phase should consist of software

upgrades and modifications of parts due to obsolescence. Their initial design should be as complete as possible so that these modifications are not extensive.

The manufacturers would like to produce a system that will require a minimal amount of refinement during its lifetime. The costs they will have to incur for these refinements should be kept at a low level. Many refinements translate for the manufacturers into resources committed to the support of the system. Also, many modifications and upgrades are perceived by the customers as quality problems and hurt the manufacturers' reputation.

The CAF maintainers, also, would like the system to operate without the need for major modifications. Very often the modifications on a system mean additional downtime. The maintainers view the system as a solution to the problem of increased downtime due to structural inspections on the A-37 aircraft; they would not like a new source of downtime to be installed on their aircraft.

In the final phase of the system's life-cycle, the main stakeholders are again the country's Ministry of National Defense and the CAF. Other stakeholders the team identified for this phase are the manufacturers and the regulatory agencies.

For the purpose of our analysis, the thesis team *assumed* that the life of the ISHMS will be at least as long as the remaining life of the A-37 aircraft (i.e. the ISHMS will not be retired before the A-37's are). As the ISHMS (and the A-37 aircraft) reaches its design life a new problem arises for the Ministry of National Defense and the CAF. The problem is how will the system be retired and disposed, and how will the lost capabilities be replaced.

Both these stakeholders will need to develop a plan for the retirement of the system. If the system has still remaining useful life could it be removed from the retired aircraft and used on other aircraft? Could it be sold to another operator who could still use it? Is the system completely useless and needs to be discarded? Are there any restrictions in the disposal of the system? These are some of the questions that need to be answered by the stakeholders. The CAF as the *customer* would prefer

the retirement and the disposal of the system to have as little effect as possible in its operations.

The manufacturers are another group of stakeholders in this phase. Very often they are involved in the disposal of their products. They have to make sure that the requirements of another stakeholder, the regulatory agencies, for this phase are being met.

4.4 Operational Concept

As the thesis team discussed in chapter 3, the development of the operational concept for the ISHMS will be done by creating sets of scenarios for the life-cycle phases of the system. The purpose of these scenarios will be to describe the view of the main stakeholders and its interaction with the system at the different phases of the system's life-cycle. The focus in these, relatively simple, scenarios is on *what* the stakeholders and the system are doing and not *how* this is being done.

For the first two phases *identification of need* and *concept definition* the thesis team developed scenarios that applied to both of them. The reason is that in the first phase, as the thesis team already mentioned, the system exists only as a vague idea in the mind of the stakeholders; this idea starts taking shape in the second phase.

Scenario: The systems engineers identify the stakeholders for the first phase of the system. The systems engineers *enter* the customer's environment and get a clear understanding of the customer's needs and how they will use the system. They prepare and discuss with these stakeholders a concept for the system. Agreement is achieved among the stakeholders on the proposed concept. The systems engineers continue the development in the next phase.

Scenario: The systems engineers try to identify the stakeholders for the first phase of the system. The CAF Flight Safety agencies are not identified as stakeholders. The proposed concept does not include the views and requirements of the Flight Safety agencies. Agreement cannot be achieved among the stakeholders. The system

engineers revise the stakeholders to ensure all involved groups are represented in the operational concept of the system.

For the next phase the *preliminary design* a possible scenario describing what the system and the stakeholders do is as follows:

Scenario: The systems engineers develop the Systems Engineering Plan (SEP) and define the *"who, what, when, where, why, and how of the applied SE approach"* [23]. They develop the integrated master plan and schedules as well as the technical performance measures. They organize system engineering, design and integration teams and define detailed roles for their members. At the same time, they translate the operational concept into the users' requirements and develop the system architectures.

Scenario: The systems engineers develop the SEP. They develop the integrated master plan and schedules as well as the technical performance measures. They organize system engineering, design and integration teams but the responsibilities and the roles of the integration team are *not explicitly defined*. This omission results in miscommunication between the teams and reporting problems in subsequent phases.

In the next phase *detailed configuration item design* a possible *scenario* unfolds as follows:

Scenario: The system design team develops the configuration item list and the design for each item. The integration plan and verification-validation requirements are defined. The physical solution of the system takes shape as the designers are considering the technologies that are going to be used. The configuration items' design is influenced by the requirements set by the manufacturers, who are also involved during this phase.

A possible scenario for the final phase of the development period, the *system integration*, is the following:

Scenario: A prototype of the system is built. The integration of this prototype proceeds as planned. During the validation testing the designers identify that some of the requirements were not addressed satisfactorily. The design team reviews the

design of the unsatisfactory configuration items. The validation tests are revised to reflect the design changes. The validation is successful and the design is approved for production.

In the *production phase* the manufacturers (contractors) and the CAF engineers and acquisition officers are the main stakeholders.

Scenario: The manufacturers get into contract with the CAF, develop a production plan, acquire the special equipment needed for the new production line, contract suppliers for the required parts and begin production. CAF engineers are checking periodically the production progress. The production proceeds as planned and the systems are completed in time.

Scenario: The manufacturers get into a contract with the CAF, develop a production plan, acquire the special equipment needed for the new production line, contract suppliers for the required parts and begin production. The suppliers cannot meet the delivery schedule. This situation causes delays in the ISHMS production. CAF engineers and acquisition officers are dissatisfied. The manufacturer is trying to find other supply sources while renegotiating the ISHMS production plan with the Air Force.

As the production of the first systems goes towards completion the *training phase* begins.

Scenario: The CAF training agencies and the manufacturer's training division agree on a training schedule for the customer's personnel. They decide that the training will take place at the manufacturer's facilities. Training courses are developed for each group of operators (i.e. maintainers, pilots, etc.) The training facility is arranged and a dummy system is built for educational purposes. The training starts and proceeds according to the schedule. The CAF operators are satisfied with the level of knowledge and practical application provided.

Scenario: The CAF training agencies and the manufacturer's training division agree on a training schedule for the customer's personnel. They decide that the

training will take place at the *customer's facilities*. The training material and aids will be developed and provided by the manufacturer; different courses are developed for each group of operators (i.e. maintainers, pilots, etc.) The training facility is arranged and a dummy system is built for educational purposes. The training begins but the trainees consider the *knowledge provided to them inadequate*. The manufacturer's personnel revise the training material and the schedule. The training is completed with a delay that causes the system deployment schedule to slip behind.

Scenario: The manufacturer's personnel and the CAF training agencies come to agreement for the provision of training in the next years after the deployment.

During the *deployment phase* the main stakeholders are the CAF and the manufacturers. Some scenarios describing this phase are the following:

Scenario: A deployment plan is arranged between the CAF agencies and the manufacturer. The location of the system installation, the equipment required, the task performance (who is going to do what), and the time schedule are defined. The deployment proceeds according to the schedule. The system is delivered and accepted on time.

Scenario: A deployment plan is arranged between the CAF agencies and the manufacturer. The location of the system installation, the equipment required, the task performance (who is going to do what), the time schedule are defined. As the installation of the system on the first aircraft is completed and the CAF personnel performs the acceptance inspection, system operation problems are revealed. The manufacturer's engineering department is involved and is trying to find a solution. The deployment schedule slips. The cause of the problem is *traced to the production* phases. The manufacturer comes up with a solution and the deployment resumes.

Scenario: A deployment plan is arranged between the CAF agencies and the manufacturer. The location of the system installation, the equipment required, the task performance (who is going to do what), and the time schedule are defined. As the installation of the system on the first aircraft begins problems are revealed. The

manufacturer's engineering department is involved and is trying to find a solution. The problems are *traced to the design phase*. The designers are involved while the deployment is cancelled. The designers find a solution to the problem. The production of the redesigned parts starts and the deployment resumes after a long delay.

Once the deployment is completed the *operation phase* begins. The CAF and the country's Ministry of Defense are the main stakeholders in the phase who are expecting the system to relieve their problem.

Scenario: The A-37 aircraft start flying with the ISHMS installed. The system functions as designed and as desired. The monitoring of the cracks and the corrosion is continuous; the data acquired from the system are accurate. The analysis performed at the ground workstation helps the engineers to assess the individual aircraft condition. The warnings generated for some aircraft prove to be accurate. After a short period of data collection a customized inspection plan for each aircraft is generated. The engineers' assessment of the fleet's condition allows them to develop a plan for the service life extension. The customized inspections have shorter duration while the components needing replacement are significantly reduced. The A-37 fleet availability increases to the desired level.

Scenario: The A-37 aircraft start flying with the ISHMS installed. The system's operations is not as desired. The monitoring of the cracks and the corrosion is *problematic*; the data acquired from the system are very often *corrupted*. The analysis performed at the ground workstation creates difficulties to the engineers in assessing the individual aircraft's condition. The warnings generated for some aircraft prove to be *inaccurate*. Maintenance is performed based on the ISHMS indications, which proves to be unnecessary. The engineers' assessment of the fleet's condition *does not* allow them to extend the A-37 aircraft service life. The maintainers are still performing the structural inspections. As a result the anticipated improvement in the aircraft availability is not achieved. The maintenance and operations agencies are dissatisfied. The manufacturers and the designers are investigating the root cause of

these functional problems. The development of a corrective action is time consuming and creates additional problems to all stakeholders.

Simultaneously with the operation phase begins the *maintenance phase*. The main stakeholders now are the CAF maintenance groups.

Scenario: After the completion of the system installation begins its operational use. There are no effects caused by the ISHMS to other aircraft systems. The number of system failures is small and the maintainers involved with its maintenance are satisfied. They believe that the troubleshooting and repair procedures developed by the manufacturer are effective, and the training provided to them adequate to maintain the system.

Scenario: After the completion of the system installation begins its operational use. The maintainers involved with its maintenance are *dissatisfied*. They believe that the troubleshooting procedures are inadequate and the system is difficult to maintain (i.e. components are hard to reach, a lot of teardown required). The downtime caused by the ISHMS failures is significant. The manufacturer's personnel are involved and are trying to improve the troubleshooting procedures.

Scenario: As the system goes into operation and starts experiencing failures the CAF Logistics agencies realize that its support is not an easy task. The parts ordering system is ineffective with long lead times and delays. The cost of the replacement parts is also high. These delays create problems in the support provided to the maintainers, while the high costs put pressure on the budget.

As more experience from the system's operations is accumulated the need for some improvements/modifications may arise. This happens in the *refinement phase*.

Scenario: The data collected from the ISHMS are analyzed and feedback is sent to the manufacturers and the designers. The system operates as designed and no further refinement is required.

Scenario: The maintainers send feedback from the system operation to the manufacturer. The manufacturer improves the ISHMS analysis algorithm and organize

in coordination with the operator an upgrade. The operators expect this upgrade to have minimal effect in the operational use of the aircraft.

Scenario: Some of the ISHMS parts supplied from commercial sources become obsolete. The manufacturer identifies the need for a modification to the system in order to replace the obsolescent parts. New supply sources are selected. The manufacturer is trying to use replacement parts that are expected to have longer life. The modification of the system is organized in coordination with the operators and executed by a manufacturers' field team. Additional training is required for the CAF maintainers on the new ISHMS configuration after the modification.

Finally in the *retirement phase* the CAF and the country's Ministry of Defense are the main stakeholders. The following scenarios describe their involvement with the system in this phase.

Scenario: As the ISHMS is approaching the end of its design life the CAF engineers must evaluate the situation and make a recommendation for the actions that will follow. They develop a plan for the retirement of the system. They examine the regulatory restrictions in order to ensure that the system's disposal will not create any conflict with the regulatory agencies. The schedule is followed and the system goes out of service.

Scenario: The CAF engineers determine that the A-37 aircraft must be retired. However, the ISHMS has still remaining useful life. Arrangements with the manufacturer are made to purchase the retired (i.e. no longer needed for the CAF) systems. The manufacturer can upgrade and resell these systems to another customer.

Scenario: As the ISHMS is approaching the end of its design life the CAF engineers must evaluate the situation and make a recommendation for the actions that will follow. They develop a plan for the retirement of the system. They agree with the manufacturer to carry out the disposal of the retired systems. As the manufacturer is trying to dispose the systems they realize that there is a conflict with the environmental regulations due to toxic material contained in the ISHMS parts. The

manufacturer is searching for a solution to neutralize the toxic substances and dispose the retired systems.

The results of the SE requirements process are presented in the following section. A structured process seven step approach is used. User provided originating requirements allow the methodical discovery and refinement of the ISHMS requirements.

4.5 Requirements Results

Manpower intensive 300 hour periodic maintenance inspections were driving up the cost of operating Cessna A-37 legacy aircraft beyond original safe life [41]. Buede's structured method of requirements definition was used to develop the originating and derived requirements for the A-37 ISHMS to reduce this maintenance cost while maintaining SOF. The structured method for creating the ISHMS requirements involved a seven step approach.

The first step developed the A-37 ISHMS operational concept. The ISHMS operational concept was the general vision of the system, a statement of capability requirements, and how the system was expected to be used (Figure 3.4). The user provided the operational concept with a series of originating requirements.

4.5.1 Vision. The generic Major Command Headquarters needed an integrated system that reduces the cost of safely operating Cessna A-37 legacy aircraft beyond design safe life.

4.5.2 Originating Requirements. The implementation of an ISHMS will reduce the current aircraft inspection burden on the maintainers. The burden shall be reduced, not necessarily all inclusive, by increasing the mean time between inspections, decreasing mean time to inspect, and/or decreasing number of inspection items, as well as reducing the risk of damage due to performing the inspections. Ideally, such system will alert the user of current and/or impending aircraft structural health fail-

ures. The system shall be reliable and accurate such that it does not adversely impact aircraft safety or maintenance. The addition of the system should maintain the SOF within the allowable parameters. Ideally, the addition of the ISHMS should not reduce the performance nor impose restrictions on the operational limits of the aircraft. The presence of the system on the aircraft should not limit the use of the aircraft in current and anticipated operational environments. The total life-cycle cost (development, acquisition, installation, operating/maintenance, and disposal) of the ISHMS should not exceed the total aircraft maintenance costs (inspections and repairs) of the structural components being monitored by the ISHMS for the extended service-life period. The average A-37 fleet flight hours are 5958 (Figure 4.7).

The estimated A-37 aircraft design life is 8000 flight hours allowing the aircraft to operate up to 10,000 total flight hours (8 years of additional usage). The impact to aircraft availability shall be reduced, when possible, by installing the ISHMS during scheduled aircraft downtime. Additionally, the need for specialized tools or additional support equipment should be kept to a minimum. The ISHMS should have a low mean time to repair and a high mean time between failures. System calibration should be required no more than once annually. Once installed, the system should be easily accessible for maintenance purposes. Additionally, maintenance of the ISHMS should not induce damage to the aircraft. The system will include an internal component failure test, i.e. self-test. The system design life should exceed twice the remaining expected aircraft life. The system should not require hazardous material handling nor disposal. Minimize ISHM integration with current legacy aircraft subsystems. As much as possible, the ISHM system shall be self contained with minimum connections to aircraft avionics and power.

4.5.3 Expectation of Use. The system should be intuitive and easy to operate. System data should be available and formatted such that it can be analyzed efficiently and easily at any maintenance or operating location. Any generated data will be archived in an external system and retrievable at a later time. Structural health

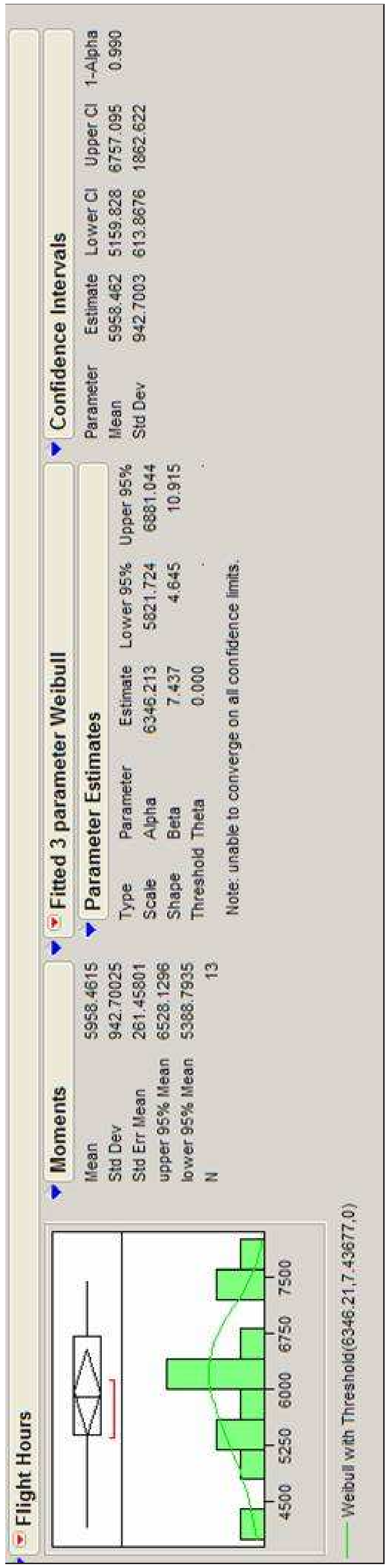

Figure 4.7: CAF A-37 Flight Hour Distribution

data will be used for extending time between inspections and facilitate planning. Industry standards for hardware connections and data formatting should be used.

The second step was the definition of the system boundary with an external systems diagram. A context diagram was created to distinguish the ISHMS boundary from the external systems (Figure 4.8).

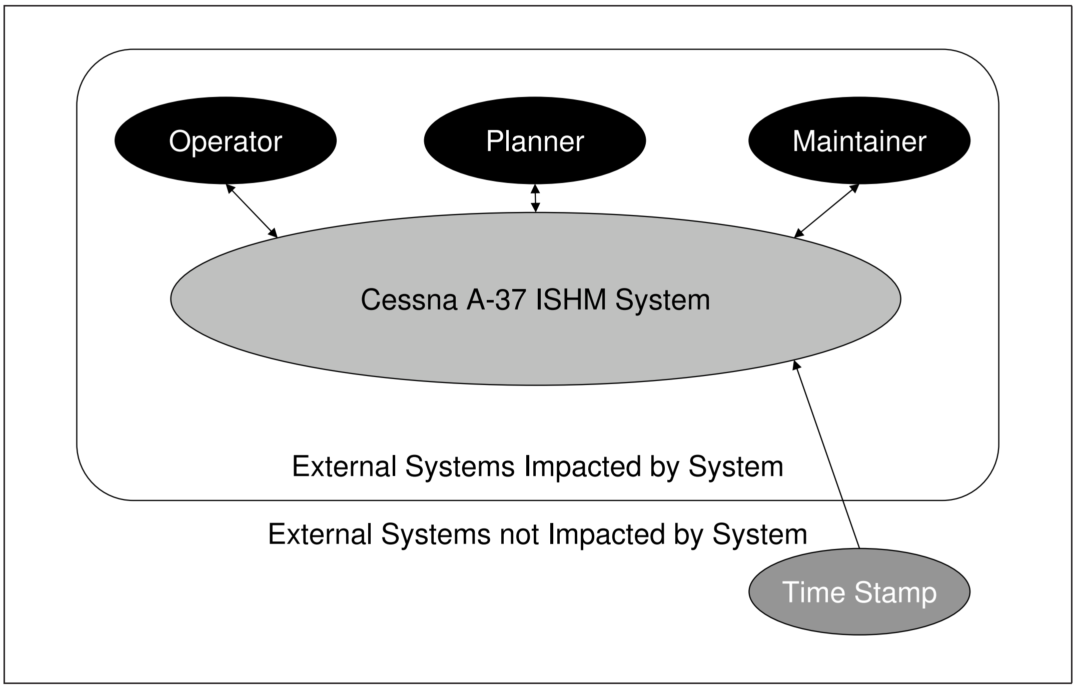

Figure 4.8: ISHMS Context Diagram

The third step was the development of the weighted objectives hierarchy and performance indices (Appendix C). This hierarchy defined cost, schedule, and performance goals the stakeholders required for an acceptable system design (Figure 4.9).

The fourth step of developing, analyzing and refining the requirements required taking the operational concept, system inputs and outputs, and combined with the objectives hierarchy to refine the originating requirements into the system requirements.

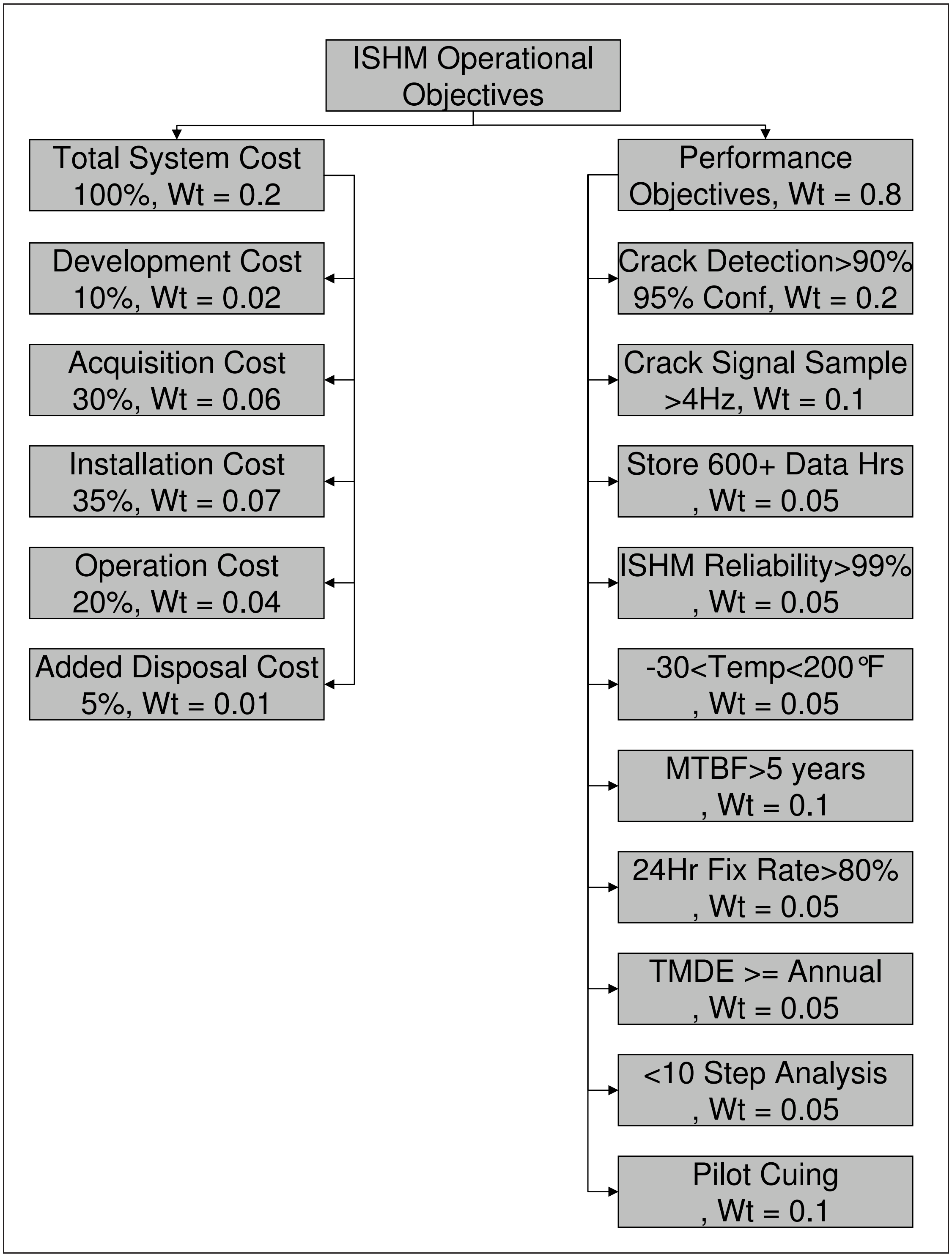

Figure 4.9: ISHMS Objectives Hierarchy

4.5.4 System Requirements.

1. Extend Service Life
2. Reduce Inspection Burden
3. Reduce Inspection Induced Damage
4. Maintain Safety of Flight
5. Reduce Cost
6. Collect Data in Real Time
7. Minimize Impact on Aircraft Operations
8. Easy to Maintain
9. Easy to Use Pilot and Maintenance Cuing
10. Minimize Development and Installation Time
11. Streamline Acquisition

The fifth step was to ensure the requirements feasibility. Feasibility was determined if the requirement was verifiable with demonstration, analysis and simulation, inspection, or instrumented test.

4.5.5 Requirements Feasibility. The *Extend Service Life* requirement was observed by analysis and simulation utilizing structural finite element analysis to predict crack growth with operations for an additional 5000 flight hours beyond design life.

The *Reduce Inspection Burden* requirement was observed by analysis and simulation utilizing the structural metamodel with a Monte Carlo simulation to predict feasibility of extending 300 flight hour inspections to a 600 hour inspection interval.

The *Reduce Inspection Induced Damage* requirement was observed by analysis and simulation tabulating the difference in number of inspections from the baseline

to the extended inspection interval with the ISHMS. The reduction in the number of inspections correlates to a reduction in the amount of inspection induced damage.

The *Maintain Safety of Flight* requirement was observed by analysis and simulation comparing the single flight hour probability of fracture of the baseline inspection interval versus the extended inspection interval with the ISHMS installed. Both values were compared to the USAF standard of 10^{-7}. The crack probability of detection of the ISHMS was observed by instrumented test.

The *Reduce Cost* requirement was observed by analysis and simulation comparing the difference in the number of 300 hour inspections of the baseline versus the status quo multiplied by the expected cost of the inspection.

The *Collect Data in Real Time* requirement was observed by analysis and simulation utilizing finite element analysis dynamic model to predict the modal frequencies of the A-37 wing.

The *Minimize Impact on Aircraft Operations* requirement was observed by instrumented test of the modified system during environmental and acceptance testing.

The *Easy to Maintain* requirement was observed by demonstration during acceptance testing.

The *Easy to Use Pilot and Maintenance Cuing* requirement was observed by demonstration of maintenance personnel using the system and instrumented test of the pilot cuing function.

The *Minimize Development and Installation Time* requirement was observed by inspection of the system design.

The *Streamline Acquisition* requirement was observed by inspection of the ISHMS design.

The sixth step was defining the qualification system requirements. The system qualification involved establishing the requirements to; validate the operational concept, verify the components & system, validate the system, and accept the system.

4.5.6 Qualification Requirements. *Extend Service Life* ISHMS will extend operation of A-37 service life beyond original design life of 5000 flight hours.

Reduce Inspection Burden ISHMS should reduce operations and maintenance cost by extending 300 hour inspections to 600 hour intervals.

Reduce Inspection Induced Damage The ISHMS shall reduce overall number of inspections proportionally reducing inspection induced damage from disassembly and inspection.

Maintain Safety of Flight The single flight hour probability of fracture should not exceed the USAF standard of 10^{-7}. The fleet total probability of fracture should not exceed 1 in 10^3 [65]. The crack detection ability of the ISHM system should meet or exceed the USAF standard of 90% detection with 95% confidence. The ISHMS should notify maintenance and operations personnel of impending failure prior to fracture.

Reduce Cost ISHMS must produce cost avoidance greater than the development, installation, and operation cost of the ISHMS.

Collect Data in Real Time ISHMS should collect crack growth data in real time at a Inquest rate of at least 4.034 Hz to enable the capture of bending vibration effects on crack growth. ISHMS should have capability to store greater than 600 flight hours of sensor readings.

Minimize Impact on Aircraft Operations Installation and operation of the ISHMS should provide a less than 10% impact on aircraft performance (weight, max speed, etc). The ISHMS modification should not impact aircraft operational requirements. The ISHMS should not reduce the number and types of mission profiles flown. The ISHMS impact to mission capability should be minimized by installation during scheduled maintenance, depot, or 300 hour inspection periods. ISHMS should not reduce the mission capable rate due to system reliability during operation. The ISHMS should operate in all environments from -30 to 200 degrees Fahrenheit.

Easy to Maintain The ISHMS should be easy to maintain with a Mean Time Between Failures aligned with projected depot schedule of once every five years. Mean Time To Repair should be should be minimized by maximizing the use of Line Replaceable Units (LRU) in the ISHMS. The LRUs should be as easily accessible as the current A-37 avionics subsystems. The 24 hour fix rate should be greater than 80%. The system should be easy to maintain without specialized tools and Material Handling Equipment. Periodic maintenance of the system should also be minimized by restricting calibration by Test Measurement and Diagnostic Equipment to no more than once annually. The ISHMS should also include a self diagnosis function to verify the status of the sensors, wiring, multiplexing, pilot cuing, and data storage.

Easy to Use Pilot and Maintenance Cuing The ISHMS should be easy to use by novice 3-level maintenance personnel. There should be no more than 3 steps to retrieve the crack growth data from the A-37 aircraft. The data should be automatically analyzed resulting in user friendly outputs of flight hours remaining until maintenance required. The ISHMS should be based on a 2-level maintenance concept with flight line maintenance troubleshooting the system and replacing LRUs. The ISHMS tasks should be easily trained with the standard tasks of downloading, uploading and interpreting the crack growth data taking no more than 10 steps to accomplish. The crack growth data should auto archive compiled data and make it available for a period of 5 years. The ISHMS should provide instant pilot cuing indicating crack growth is approaching structural failure.

Minimize Development and Installation Time The ISHMS integration with current aircraft subsystems should be minimized to reduce the effect on aging wiring and reduce requalification testing of the A-37 aircraft. The ISHMS should be self powered with no requirement for aircraft power. The ISHMS should not connect to the aircraft electrical system. The modification time and cost should be minimized to expedite installation of the ISHMS on the A-37 aircraft. ISHMS install shall be accomplished in coordination with current scheduled maintenance activities to minimize the impact

on aircraft availability. Expertise required to install the ISHMS should be no greater than that of a contractor/depot field team.

Streamline Acquisition The ISHMS design life should be greater than the projected remainder of A-37 aircraft life (i.e. 4000 flight hours). ISHMS should utilize commercial connections and industry standards wherever practical. The ISHMS should not significantly increase the hazardous waste disposal requirement of the A-37 aircraft. Finally, the basic system design should be general enough to use on other aircraft.

The seventh and final step was obtaining the sponsor approval of the requirements. The primary sponsor was unavailable so the requirements were validated through thesis advisors, AFRL, and SAF/IARL.

The results of the SE process architecture products are presented in the following section. Decomposition of the requirements into: inputs, outputs, controls, mechanisms, and functions forms the basis of the architectures.

4.6 DoDAF Architectures

In Chapter 3 the team discussed what are system architectures, their importance, and the methodology used to develop the architecture products. During this section of Chapter 4, the architecture products will be presented along with a brief description on the development process for each. Most architecture products were created using the System Architect software known as Popkin. There are a number of existing computer-aided system engineering software tools that facilitate architecture development. For example, the software package known as CORE is very popular among the SE community for its ease in the creation of IDEF0 diagrams. However, the thesis team decided to use the Popkin software because it has built-in rules for creating most of the DoDAF architecture products, thus simplifying significantly the whole architecture design process.

4.6.1 All-Views Architectures. The first products required by DoDAF were the AV-1 and AV-2, which are not exactly architectures, but rather textual definitions and description of the problem, purpose and scope of the architecture products to follow. Basically, the AV-1 places the boundaries of the architecture and is depicted in Figure 4.10. The AV-2, also known as the Integrated Data Dictionary, is a glossary with definitions of terms used in the architectures. For the most part, each item in the graphical architectures has an entry in the AV-2, which is presented in Appendix B.

Identification

Architecture Title: ISHMS Requirements Identification

Architects: AFIT GSE-06M, Section 1, ISHMS Thesis Group

Purpose

Problem Description: aging aircraft are approaching or exceeded the end of their design life; users want to safely extend the life of these aircraft while minimizing the downtime due to inspections and maintenance; a low-cost integrated structural health monitoring system that provides at near real-time feedback has been identified as the potential solution.

Purpose: to apply the systems engineering approach to the process of requirements identification for the development and acquisition of an ISHMS for aging aircraft

Scope: This architecture depicts broad ISHMS requirements and information exchanges

Figure 4.10: AV-1 Architecture

4.6.2 Operational Architectures.

4.6.2.1 OV-1: Archi-toon. The first architecture product the thesis team produced is the OV-1, also known as the archi-toon. The OV-1 (Figure 4.11) depicts an A-37 at the center symbolizing the target aircraft for which the ISHMS is being developed. The circle around the A-37 represents the system boundaries that will be directly affected by the development and implementation of an ISHMS. Notice that the circle is divided into four different areas, namely: aircraft monitoring, data management, aircraft operations, and aircraft maintenance. The first two areas at the top represent ISHMS design characteristics and their interaction is shown with

a lightning. The remaining two areas, shown at the bottom, represent systems that would have to evolve and adapt to the new capabilities provided by the ISHMS. All four areas will be thoroughly explained in subsequent paragraphs. Finally, the area outside the circle is labeled external systems and symbolizes supporting systems that may interact with the ISHMS, but will not be affected by the ISHMS. An example would be GPS satellites providing GPS time for ISHMS data time-stamping or a communications network relaying aircraft health status to a ground monitoring station. The satellite and radar systems shown in the archi-toon were drawn only for artistic purposes and by no means represent a pre-defined ISHMS concept.

Figure 4.11: OV-1 Architecture

4.6.2.2 OV-5: Operational Activity Diagram. The next architecture is the OV-5, also known as the operational activity model or IDEF0. An OV-5 can also be presented as a node-tree diagram. The main difference between the two formats is the level of detail in the information presented. A node tree only presents the functional decomposition whereas the operational activity diagram shows the

decomposition as well as the inputs, controls, outputs, and mechanisms (ICOM) for each of the functions. Both OV-5 formats will be shown for the benefit of the readers. The node tree diagram (Figure 4.12) can be thought of as a roadmap of the IDEF0 diagrams.

The thesis team started the OV-5 development by first defining the main purpose of the architecture, which is to provide a process that would help identify the ISHMS requirements. As such, this activity became the context diagram and is shown in figure 4.13. In other words, by the time the OV-5 is fully explained, the reader should have a clear understanding of the activities the thesis team recommend be performed when trying to identify design requirements for the development of an ISHMS.

At this point is worth mentioning that all OV-5 diagrams follow Popkin rules which include not having more than four ICOM arrows on any one side of a function box nor having more than six function boxes in any one diagram page. The purpose of these rules is to avoid clutter and confusion in the architectures. Also, the reader will notice some of the ICOM arrows contain parentheses. These parentheses denote what is known as tunneling, meaning that the respective ICOM is not present in its parent diagram. In most cases, tunneling becomes necessary in order to avoid clutter in the parent diagram. Usually, tunneling increases as the number of layers of decomposition increases.

Next the thesis team decomposed the context diagram into four major functions or activities that a hypothetical ISHMS should be expected to perform, namely: the structural monitoring requirements function, the data requirements function, the operational requirements function, and the maintenance requirements function (Figure 4.14). The structural monitoring function refers to the user requirement of detecting structural failure of an aging aircraft without human intervention. The thesis team determined that the only feasible way to automate this process and satisfy this user requirement was by using sensors onboard the aircraft. All decisions about the sensors (i.e., placement, quantity, properties, sensitivity) fall under the monitoring function.

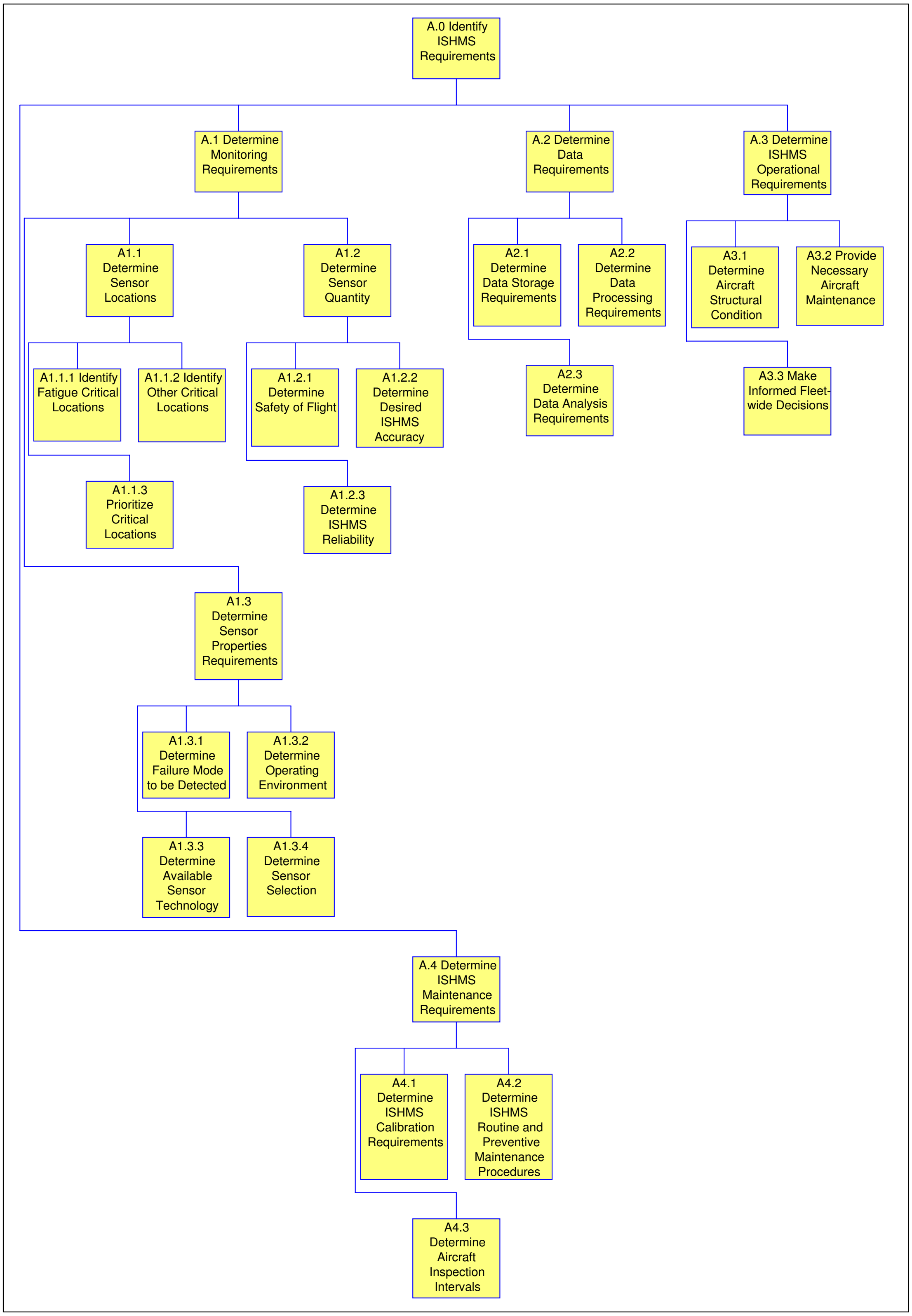

Figure 4.12: Node Tree

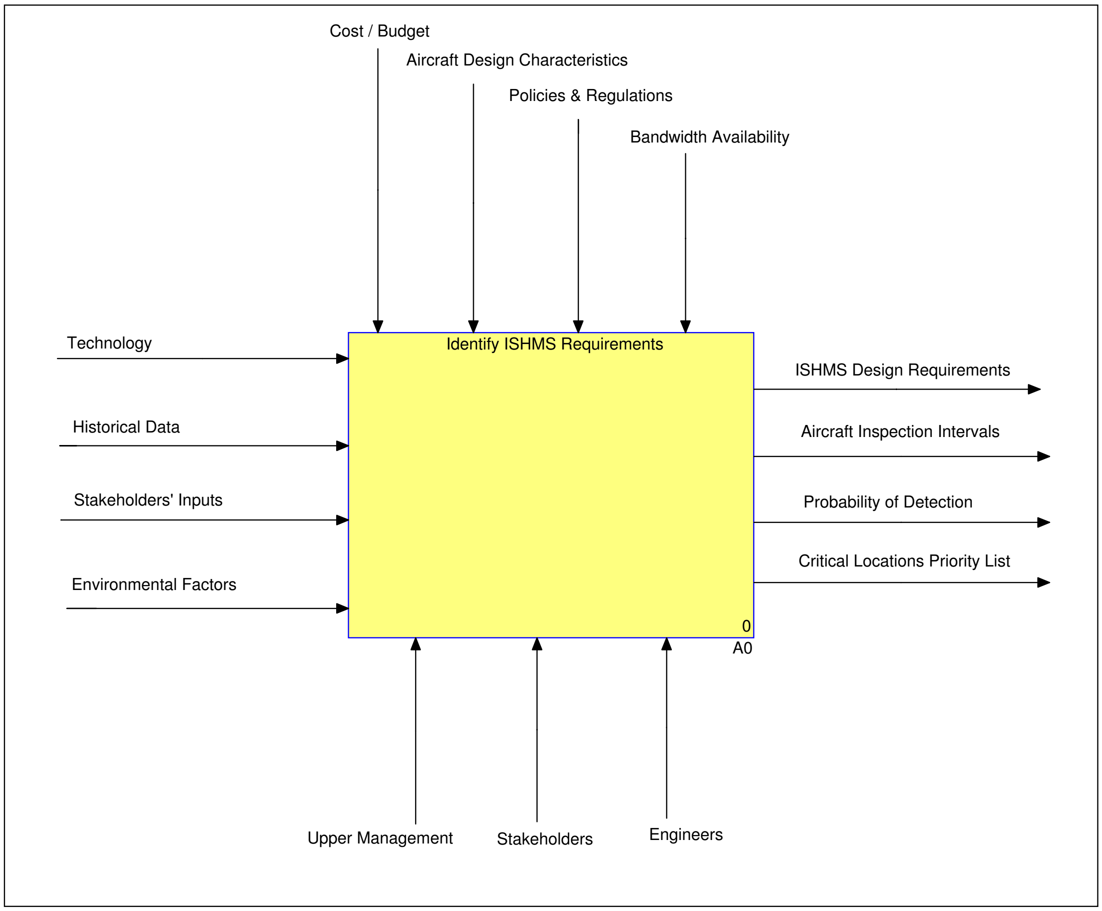

Figure 4.13: A0 Architecture

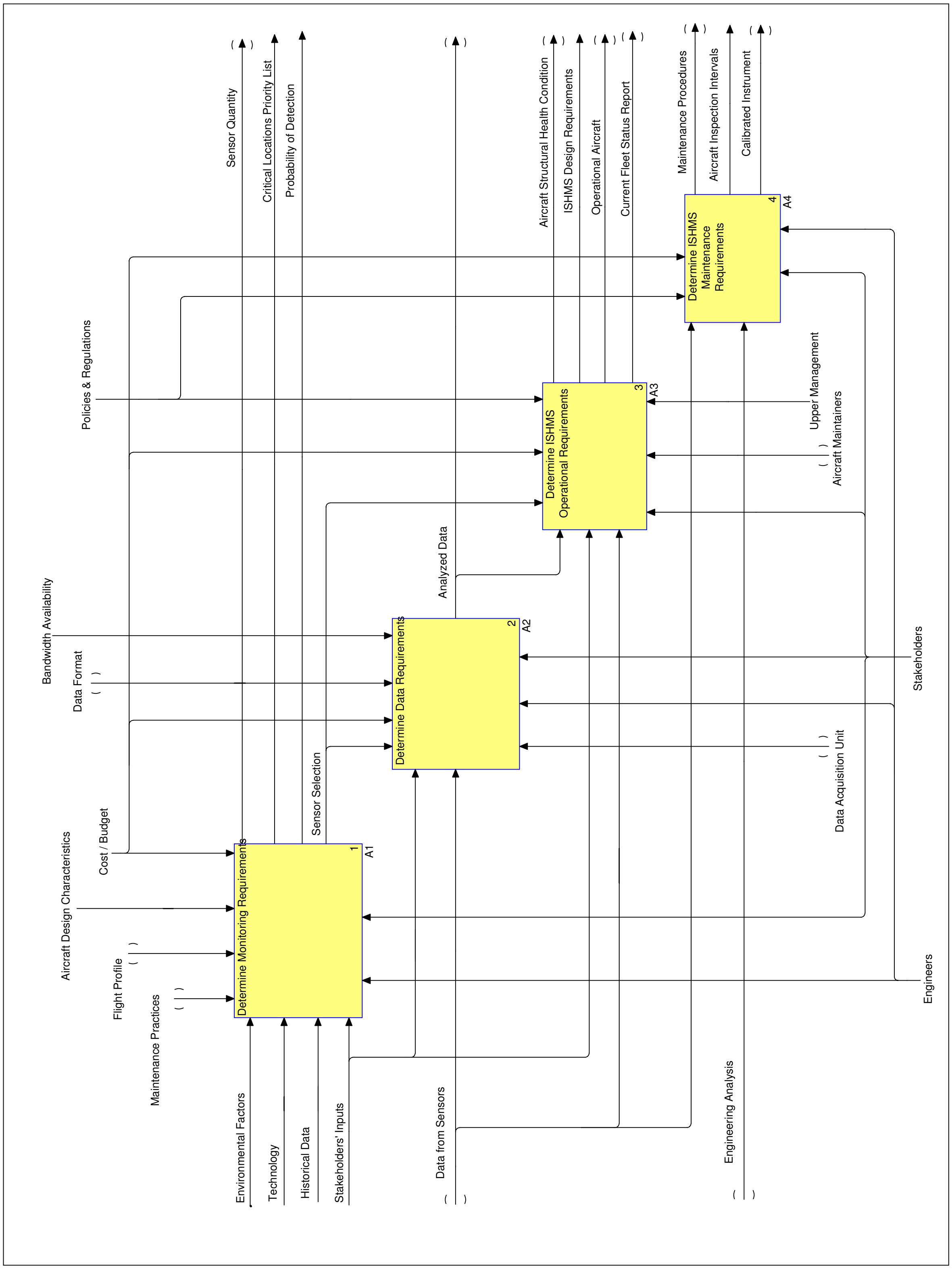

Figure 4.14: A-0 Architecture

Another major function is the data requirements function, which deals with decisions about data acquisition, handling and processing. Next is the operational function, which captures user preferences about the operational use of the hypothetical ISHMS. Lastly, the maintenance function has to do with decisions about sustaining, validating, and maintaining the system. Initially, the thesis team thought that operations and maintenance requirements could be lumped into one single function, especially when considering the CAF A-37 fleet of only 13 aircraft. However, the integration of an ISHMS to a larger fleet of aircraft and a more complex organizational structure, such as that of the USAF, would certainly justify the separation of the two functions. Thus, the thesis team decided to separate the two functions so the architecture would fit into a larger number of possible operational scenarios.

Next, the thesis team decomposed the monitoring requirements one more layer (Figure 4.15). The thesis team determined that the best way to implement an ISHMS would be through the use of a sensor network capable of detecting structural failures in various FCLs of an aging aircraft. Based on this assumption, the monitoring requirements were decomposed into three main functions. First function was to determine the location of each sensor of the ISHMS sensor network. Second function was to determine how many sensors were needed. The last function was to determine requirements for the type of sensor needed on each of the sensor locations.

The monitoring requirements were decomposed one more time (Figure 4.16) starting with determining sensor location requirements. Possible sensor locations were divided into two general categories: fatigue critical locations and other critical locations. By doing this, the thesis team purposely opened the door to monitor other aircraft components that may capitalize on the ISHMS development. Sensor locations will most likely be determined by compiling historical data on the maintenance and inspections performed on the airframe, although some stakeholders may provide justification for other specific locations. Using the A-37 as an example, historical data can be found at Hill AFB through the MAPA Engineering Analysis Division, by compiling the data from flight-line maintenance records, through interviews of pi-

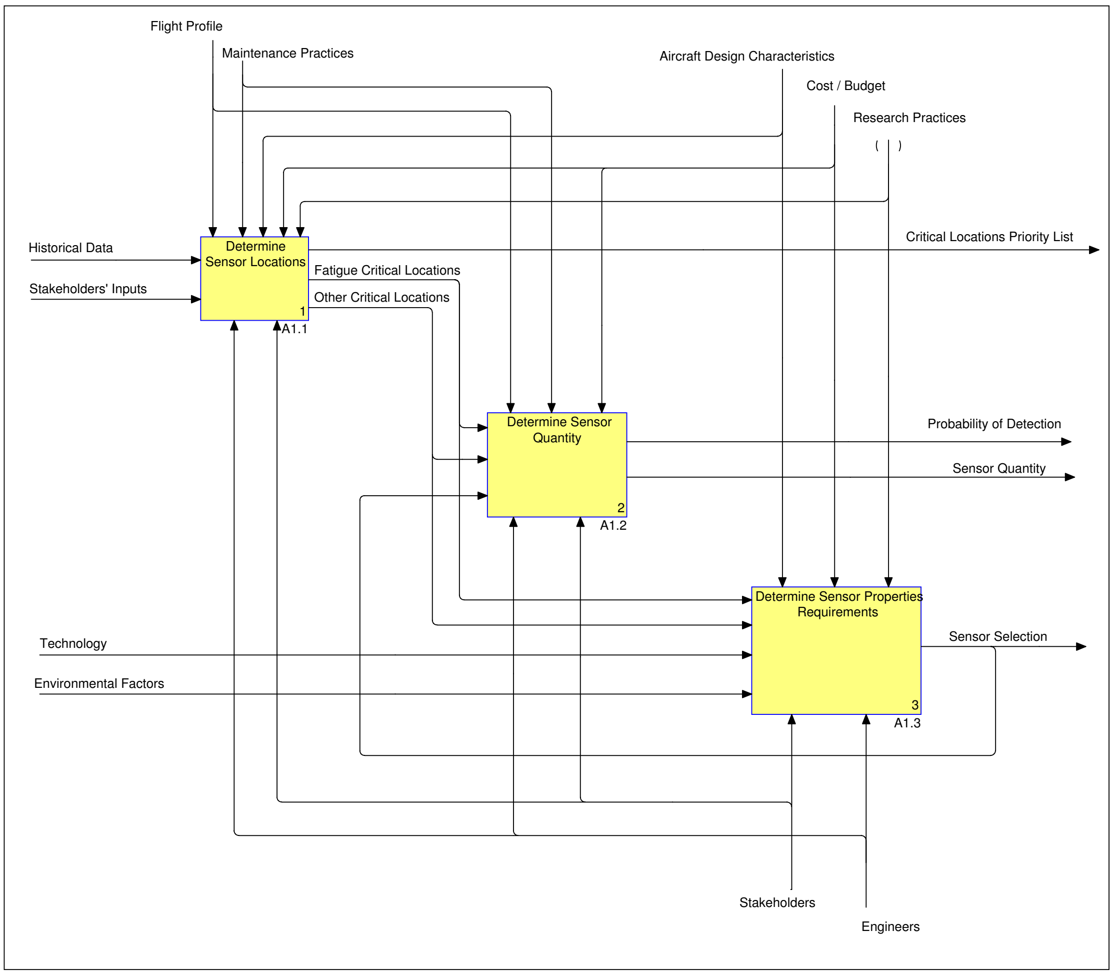

Figure 4.15: A-1 Architecture

lots and maintainers, and/or contacting the depot or equivalent services organization. The list of potential critical locations will depend on the thoroughness of the research conducted, the quality of the maintenance practices, and the level of aggressiveness of the flight profiles being flown. In addition, specific aircraft design characteristics may limit the ISHMS options as well as the budget may impose a limit on the amount of locations being monitored. The overall goal of this activity should be to end with an accurate list of critical locations and prioritize the list in order of importance. Obviously, emphasis should be placed on those locations that have a higher probability of occurrence and a higher level of risk. A risk management analysis of all critical locations should be appropriate to accomplish this activity. The mechanisms responsible of accomplishing this task are the stakeholders and any engineers hired to do the research job.

In addition to finding which locations should be monitored, it is necessary to find out how many sensors are adequate to get the job done since it may be necessary to place more than one sensor per critical location. This introduces the next decomposition diagram (Figure 4.17). The amount of sensors will most likely be dependent upon the desired SOF, accuracy, and reliability of the ISHMS in detecting failures. By accuracy of the ISHMS the thesis team refer to the confidence level on detecting a failure. Users may have an input in this activity, but the weight of the decision will rely primarily upon engineering analysis backed up by established safety regulations and policies. Cost will most likely be one of the most limiting factors in this decision since there is a direct proportional relationship between the amount of sensors and the total cost of the system.

The last function within the monitoring requirements was the determination of sensor properties requirements. This is a very important function because it deals with tailoring each sensor of the network according to the failure mode that needs to be detected and the environmental conditions (both internal and external) that the sensor must withstand. Failure modes can be due to a number of conditions including corrosion, stresses, torques, extreme temperatures, vibration, or any other condition

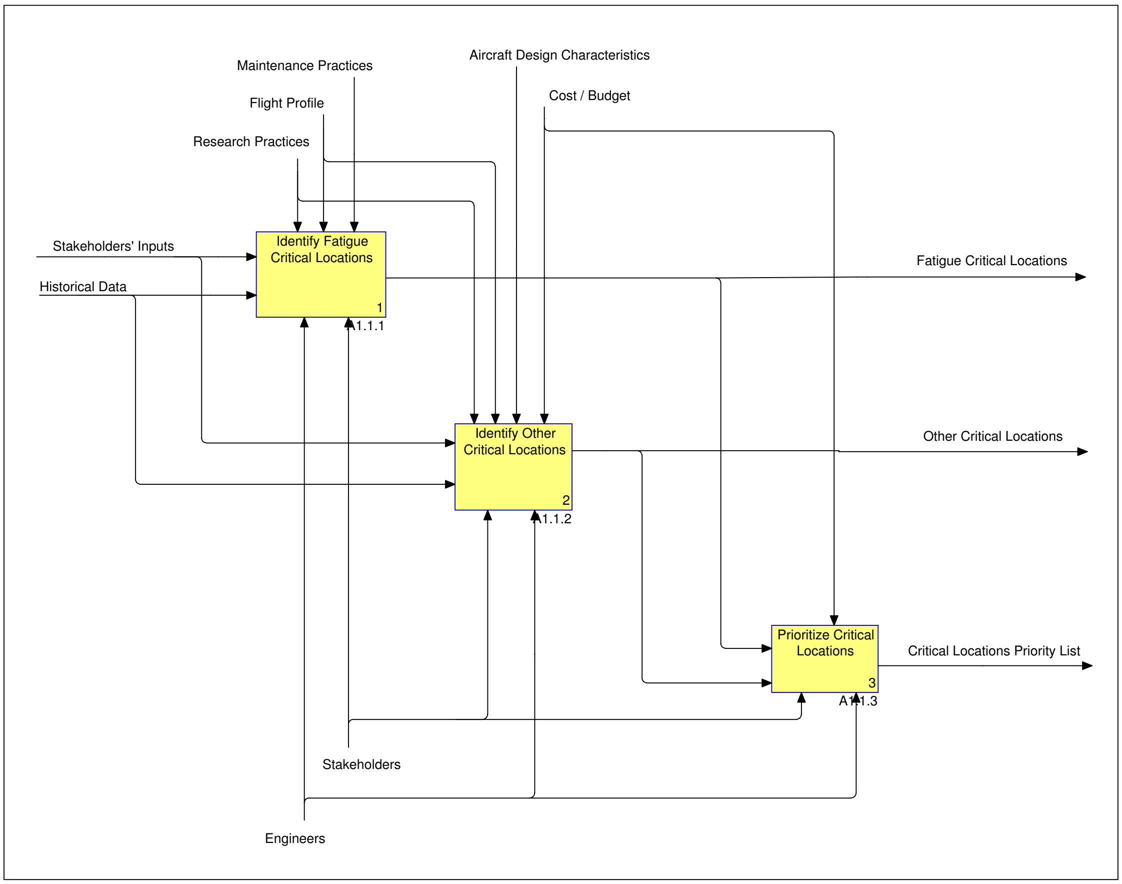

Figure 4.16: A-11 Architecture

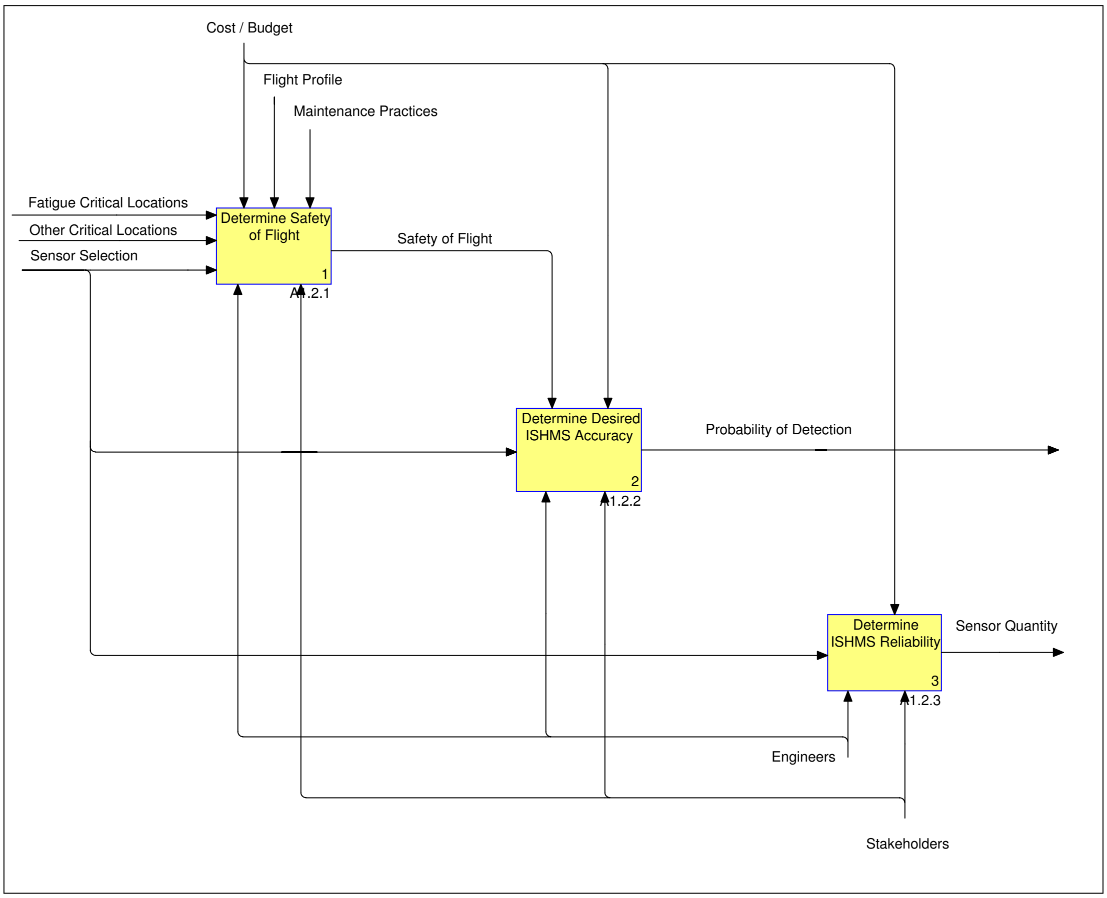

Figure 4.17: A-12 Architecture

that weakens a structural member to the point of catastrophic failure. For example, if a sensor is placed near the wing root attachment on an A-37, then the sensor must be able to work properly under extreme temperatures and vibration of its surrounding environment as a result of the proximity to the engine.

The decomposition of the sensor properties function (Figure 4.18) start with determining the failure mode that needs to be detected, since different failure modes will most likely require different sensors. The next step is to identify the internal and external environmental factors to which the sensor will be exposed for each of the locations. An example of an internal or localized environmental factor would be a critical location that is submerged in hydraulic fluid, or any other condition that results from the sensor being placed onboard the aircraft. External factors refer to the external operational environment to include weather conditions. For example, proximity to sea water may promote corrosion problems, or a dusty environment may require a sensor with additional protection from the elements, and extreme temperatures may affect the electronic properties of the sensor, thus resulting in false readings. Another activity within the sensor properties function is to determine the technologies that will be incorporated into the ISHMS. As a result, sensor selection will certainly be limited by the monitoring technologies available. Existing technologies would be more readily available on the market and most likely be cheaper than emerging technologies. Finally, after taking into consideration the failure mode, environmental factors, and available technologies, then a sensor can be tailored and matched to a specific location with cost being another limiting factor. The stakeholders must realize that there is enormous potential for trade-off opportunities to be considered when making decisions about sensor selection and placement.

Once the sensor network is in place, then the next major ISHMS function to be decomposed is the data requirements function (Figure 4.19). The thesis team divided data requirements into three sub functions: data storage requirements, data processing requirements, and data analysis requirements. Data storage requirements are directly correlated to the quantity of sensors that compose the ISHMS; therefore,

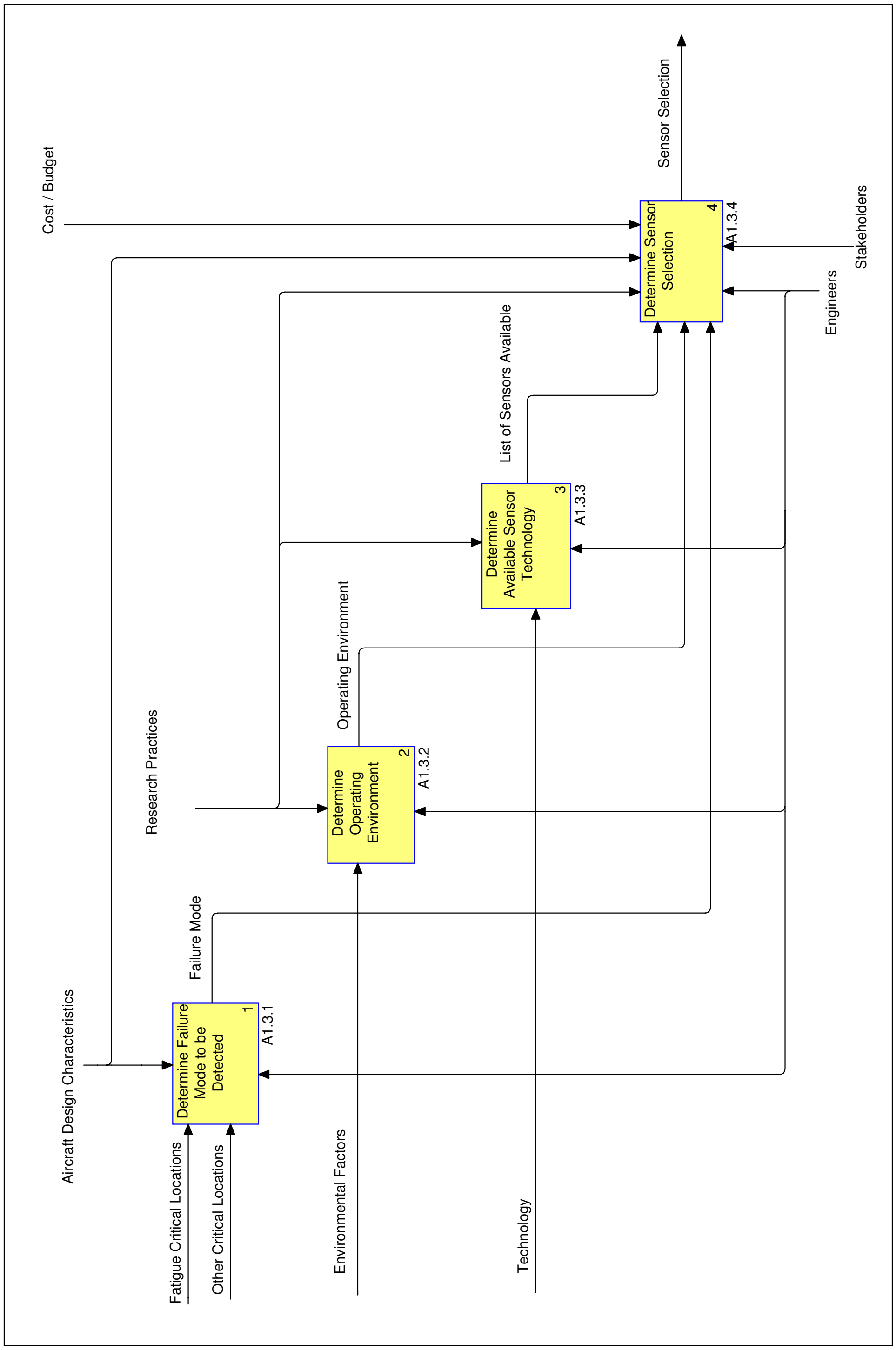

Figure 4.18: A-13 Architecture

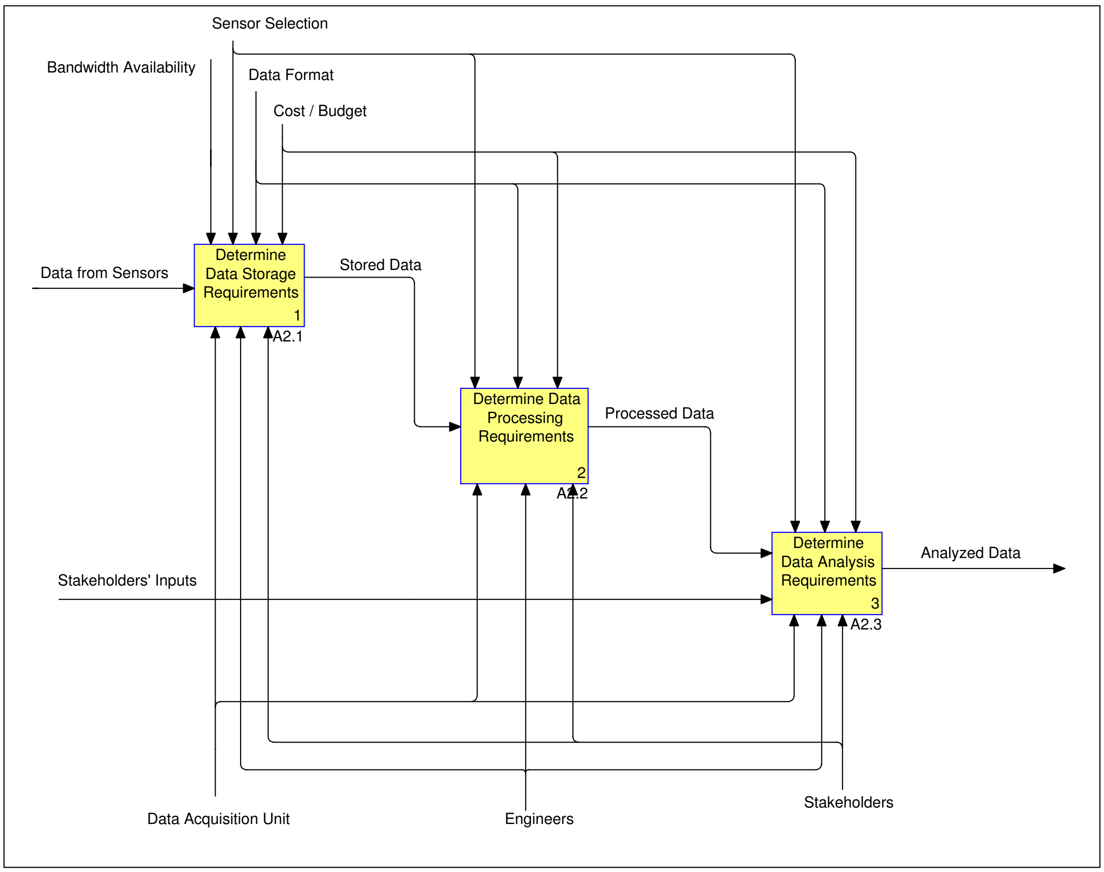

Figure 4.19: A-2 Architecture

data storage requirements will increase as the quantity of sensors increases. Each sensor outputs raw data that must be stored and sorted for future processing. The limiting factor in the data storage requirements may come from various sources, but at least bandwidth availability is definitely a potential limiting factor. Once the data has been properly and securely stored, then it needs to be processed. Data processing requirements may include sorting, synchronizing, and filtering the raw data. In other words, each data string must be identified with information such as the sensor it came from, the time of the measurement, and determining whether the data string falls within the range of possible or acceptable values. The processed data must then be manipulated and analyzed. Data analysis could be automated, manual, or a combination of both. Particular attention must be given to identifying data analysis requirements since these decisions will greatly influence the ISHMS development and design. Furthermore, if the ISHMS must interact with any legacy systems, then there will be a greater potential for unintended circumstances such as data compatibility issues. Considering the vast amount of possibilities for performing data analysis, the thesis team decided to create several hypothetical operational scenarios. The main purpose of the operational scenarios was first to investigate the various ISHMS realizations and second to avoid steering the ISHMS design in any particular direction. For example, one operational scenario may be that the ISHMS provides continuous real-time measurements and a dummy-light or visual display in the cockpit signals the pilot that there is a potential structural problem. In this scenario, the pilot is immediately aware of the problem and can react according to the emergency procedures. Another scenario is one where the sensor data is up linked via a communications system (i.e., satellite, Link-16, etc.) and down linked to a central processing ground station. In this scenario if a problem is detected, then the control tower personnel will be notified and they will take action to safely ground the aircraft by providing pilots with emergency procedures. Another possible operational scenario is one where the ISHMS is passively collecting sensor data and at the end of the flight or mission a data logger would be responsible for downloading the ISHMS from the aircraft and

into a database for an automated analysis. In this scenario, any potential problems will be known and handled after the fact, thus limiting the potential for immediate risk avoidance. However, this last scenario may be the cheapest and simplest option to implement. Many other scenarios are possible, but it will be up to the stakeholders and engineers to make those trade-off decisions, which will be constrained by the amount of money available.

The third major functional decomposition (Figure 4.20) deals with determining ISHMS operational requirements. The team's main concern within this function was exploring the events unfolding after the ISHMS data had been analyzed. This involved determining potential information exchanges and responsibilities among or within organizations. This external activity was included because the decisions made in this step may influence the final outcome of the ISHMS design. Again, given the wide range of possibilities, hypothetical scenarios were developed to avoid the risk

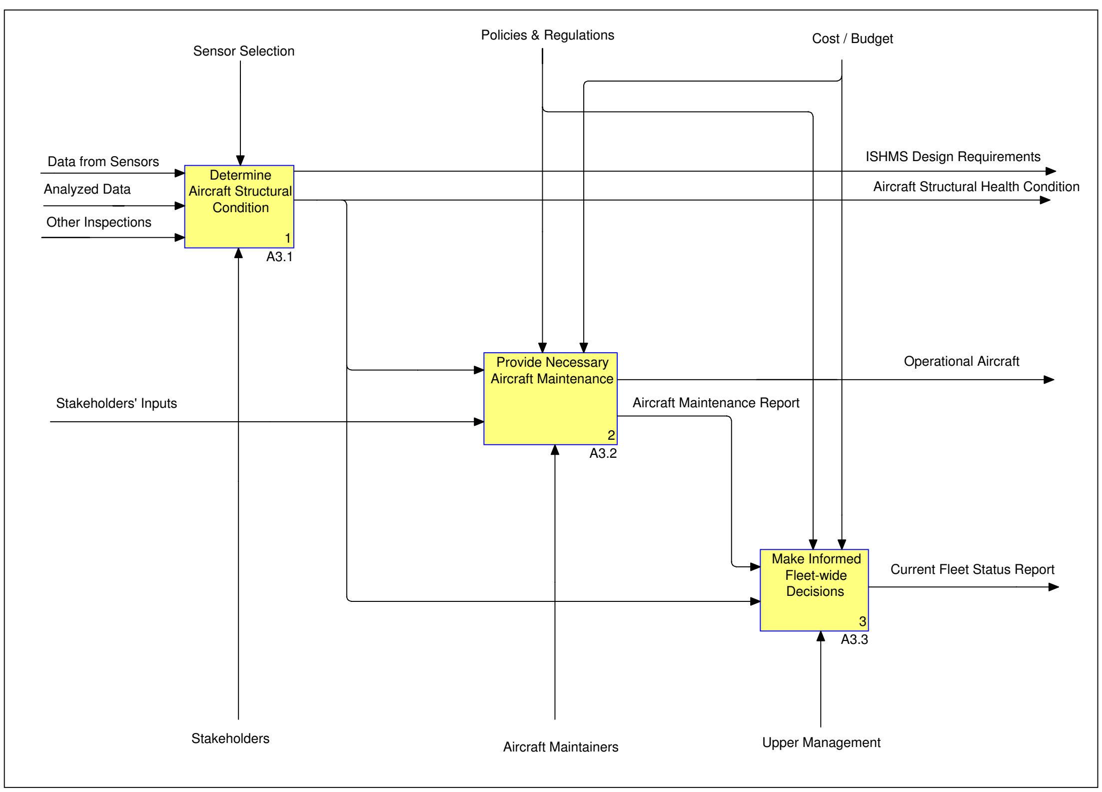

Figure 4.20: A-3 Architecture

of suggesting a specific solution. A possible scenario is one in which the ISHMS is used to assess the structural health of individual aging aircraft as a way to shift from preventive to condition-based maintenance. In other words, instead of inspecting and performing preventive maintenance every number of flight hours, continuous structural monitoring may eliminate the need for inspections and delay maintenance for when it is really needed. In this scenario, the benefits of having an ISHMS can be measured from the potential for savings (i.e., cost avoidance) on operations and maintenance in addition to the resulting increase in aircraft availability. A more complex scenario would be an ISHMS data repository that analyzes usage trends of a fleet of aircraft and suggests the rotation of aircraft between different organizations to keep the wear and tear of the fleet even. For example, ISHMS may suggest that specific F-15C tail numbers from Air Combat Command be rotated with specific F-15 tail numbers from Air Force Materiel Command (AFMC) in order to even out and maintain an optimal safety and operational status throughout all organizations; assuming AFMC aircraft flight profiles are less severe. Obviously, the latter scenario would require extensive strategic and tactical planning as well as the buy-in of higher management before being implemented. In addition, an ISHMS may be used to introduce more efficiency and control in the planning and scheduling of aircraft maintenance activities. For example, data analysis may be able to forecast the amount of flight hours left on an aircraft before it is due for maintenance. Maintainers and flight commanders can then plan accordingly the flying schedule. In addition, the ISHMS may be able to point out those locations that will require maintenance in the near future so that all maintenance can be performed at once; without the need for inspections that usually involve lengthy invasive procedures.

Finally, the last functional decomposition (Figure 4.21) was determining the ISHMS maintenance requirements. This includes installing, repairing, validating, calibrating, and other maintenance of the ISHMS. Depending on the complexity and technology of the ISHMS, some of these services may be performed on-site or they may require mobilizing the aircraft to specialized facilities. The level of maintenance of

the ISHMS will mostly depend on the level of reliance on the ISHMS. If for example, the time interval between inspections is to be increased as a result of having an ISHMS then this would require a more robust system and probably a stricter ISHMS maintenance schedule. One way to increase the robustness or reliability of a system is by adding redundancy, which in turn demands a higher cost and complexity.

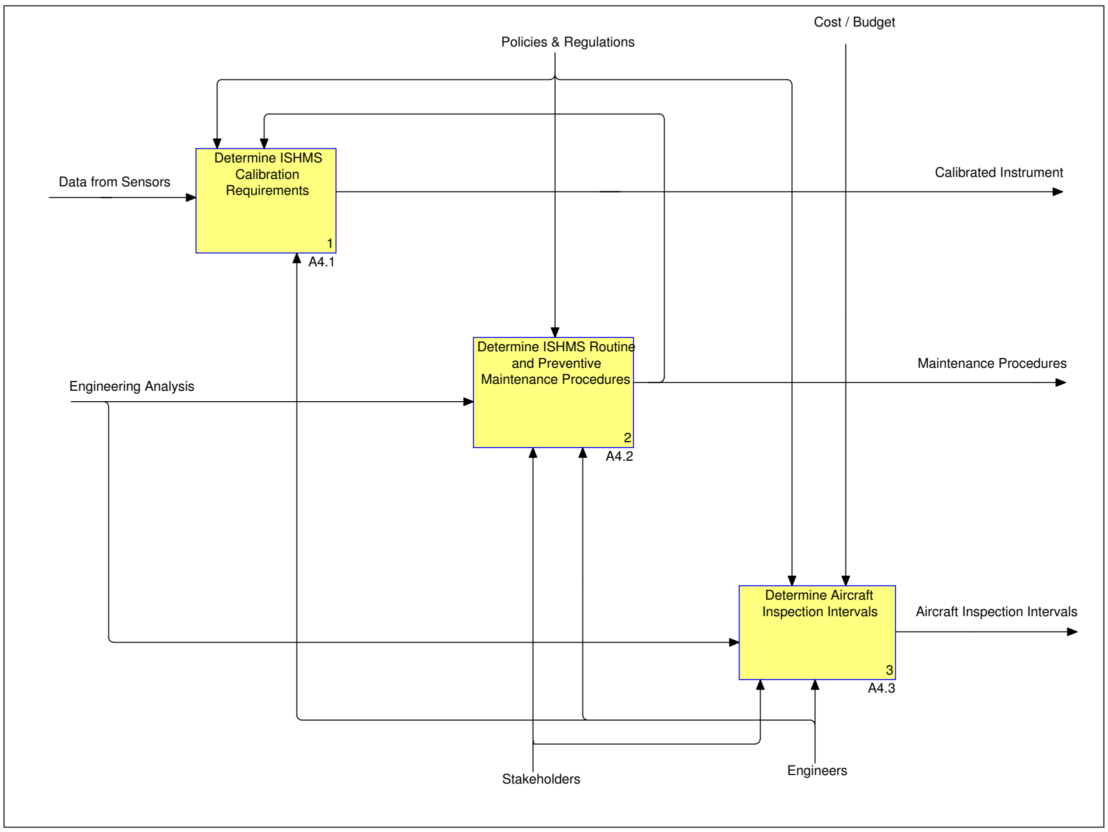

Figure 4.21: A-4 Architecture

4.6.2.3 OV-2: Node Connectivity Diagram. Next architecture developed was the OV-2 (Figure 4.22), also known as the Operational Node Connectivity Description. This diagram depicts the overall system nodes and the information exchanges between the nodes. The OV-2 shows five operational nodes, namely: the monitoring node, the data management node, aircraft operations node, aircraft maintenance node, and the external systems node.

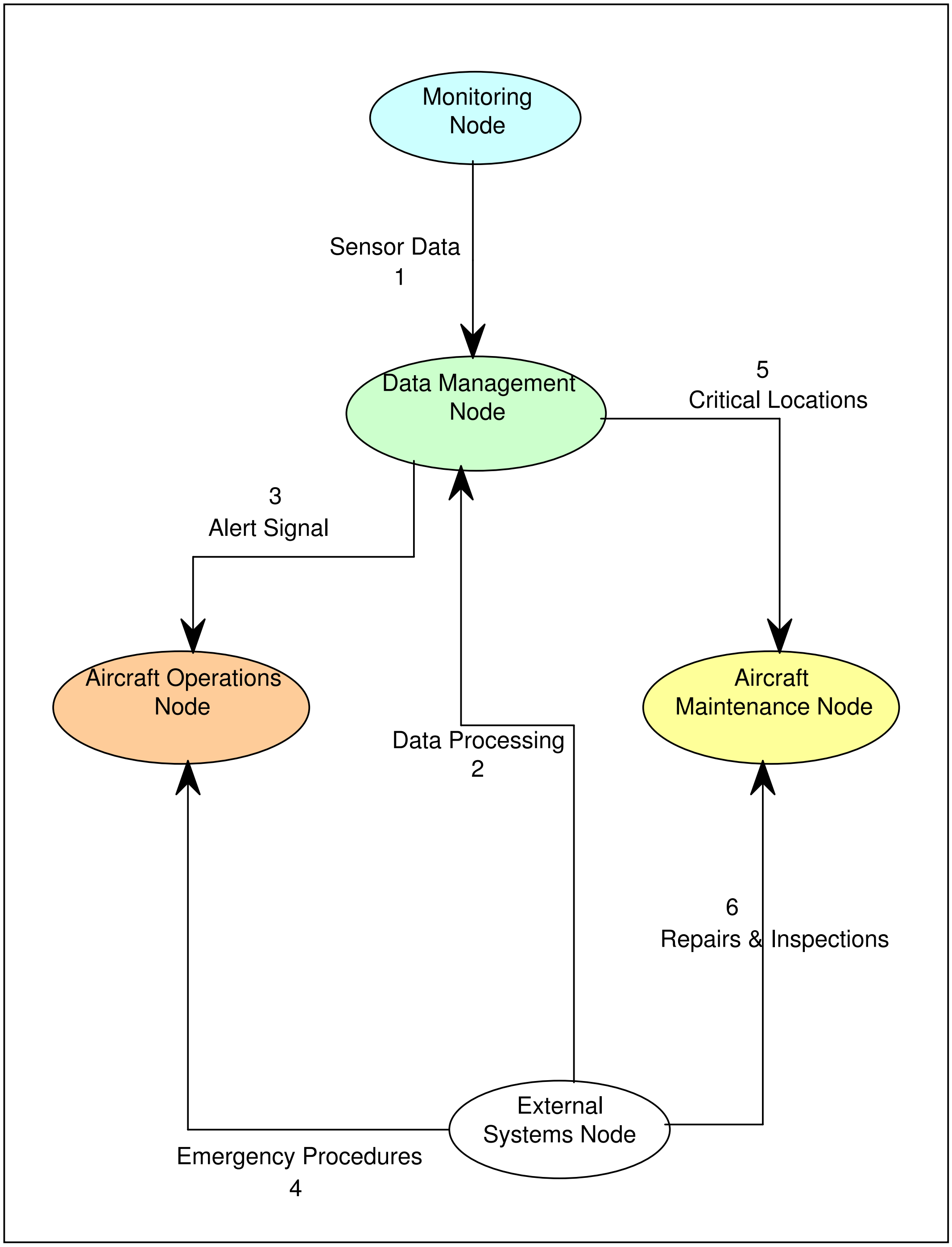

Figure 4.22: OV-2 Architecture

Notice the similarity between the ISHMS operational functions in the OV-5 and the operational nodes in the OV-2. Also shown in the OV-2 are the information needlines connecting the nodes; six needlines were identified. The first needline connects the monitoring and data management nodes. This represents the raw sensor data going into the data acquisition unit. Data processing and analysis are assumed to occur in the data management node, which could be a system or organization. The external systems node is feeding the data management node with a data processing needline. This particular needline may represent external data used for time-stamping of the raw sensor data (e.g., GPS time) or it could represent data logger feeding into an ISHMS repository. The actual meaning will depend on the final ISHMS solution. Then the data management node is responsible of alerting the aircraft operations node of potential structural failures. The aircraft operations node could be either the pilot flying the aircraft, control tower, an ISHMS data analyst, or a combination of these; it will all depend on the final ISHM design. In addition, the data management node will pinpoint the aircraft maintenance node the specific locations that require maintenance. In some instances, aircraft repairs and/or inspections may require external involvement (e.g., aircraft depot or contracted experts) and for this reason there is a needline shown going from the external systems into the aircraft maintenance node.

4.6.2.4 OV-3: Operational Information Exchange Matrix. Then the thesis team developed the OV-3, also known as the Operational Information Exchange Matrix. This architecture product is textual and provides information about the OV-2 needlines. Basically, this matrix shows the same information that was described in the previous paragraph. Thus, the OV-3 is shown in Figure 4.23 and the reader is referred to the previous paragraph for its interpretation.

4.6.2.5 Remarks. So far, the thesis team have shown the development of the AV-1, AV-2, OV-1, OV-2, OV-3, and OV-5. According to the DoDAF requirements for an integrated architecture, the thesis team would still be missing the SV-1 and TV-1. In addition, the DoDAF suggests the SV-5 matrix for an acquisition de-

Needline Identifier	Needline Name	Content	Scope	Accuracy	Language	Sending Op Node Name	Receiving Op Node Name	Mission/Scenario	Transaction Type	Triggering Event	Criticality
1	Sensor Data	Raw Sensor Data	Hypothetical ISHMS	seconds	Digital	Monitoring	Data Management	Structural Health Assessment	Network	Active Continuous Collection	High
2	Data Processing	Processed Data	Hypothetical ISHMS	mili-seconds	Digital	External Systems	Data Management	Structural Health Assessment	Collaborate	Active Continuous Data Log	High
3	Alert Signal	Alert Signal	Hypothetical ISHMS	mili-seconds	Visual Display	Data Management	Aircraft Operations	Catastrophic Failure Avoidance	Direct	Structural Failure	High
4	Emergency Procedures	Control Tower	Hypothetical ISHMS	minutes	English	External Systems	Aircraft Operations	Catastrophic Failure Avoidance	Collaborate	Airborne Emergency	High
5	Critical Locations	Failure Locations	Hypothetical ISHMS	days	Engineering Views	Data Management	Aircraft Maintenance	Problem Areas Identification	Collaborate	ISHMS Failure Indication	High
6	Repairs & Inspections	Maintenance Procedures	Hypothetical ISHMS	days	English	External Systems	Aircraft Maintenance	Problem Solution	Collaborate	Tasking Order	High

Figure 4.23: OV-3 Architecture

velopment. However, all these remaining products require knowledge on the physical systems and interfaces that make up the ISHMS, all of which is out of the scope of this thesis study. As such, the thesis team decided to limit the architecture development to the products that have been developed so far. As a final note to the reader, even though this may seem like a straight-forward architecture, its development was far from straight-forward. There were several *false starts* and iterations before arriving to its current state. Ensuring that the OV-5 was balance was not an easy task, even when Popkin pinpointed the errors. Furthermore, some necessary activities, such as the training activity, were intentionally omitted because they would require more knowledge on the physical characteristics of the system in order for the architecture to provide insightful information. Nevertheless, the requirements identification process streamlined in this architecture should be able to guide the reader to ask the right questions to the proper stakeholders. Eventually, the identification of ISHMS design requirements would reduce the number of possible ISHMS realizations and lead into trade-off studies for ultimate determination of the final ISHM solution.

The results of the structural model are presented in the following section. The benefit analysis is composed of a structural model that feeds into both a baseline 300 hour simulation and ISHMS modified simulation.

4.7 Structural Model Scope of Work

The comparison of the baseline Cessna A-37 300 hour inspection schedule versus the extended inspection schedule with an ISHMS installed required the development of a structural model to predict the stress occurring at a FCL. The aircraft usage profile (flight spectrum) was established along with a typical weapons loadout to estimate crack growth and determine aircraft service life (how many cycles the wings can be loaded until fracture). Countries can save maintenance resources by maximizing the inspection interval of the aircraft currently in their inventory while maintaining SOF at the same level as the current 300 hour inspection interval. Flight profiles and the amount of weapons carried cannot be modified without negatively affecting the mission, so the stress model at the FCL was determined with the pylon weapon loads as the design variables. Each weapon pylon location has maximum load ratings, but this structural model determined the stress applied at a FCL from the applied weapons load and flight profile.

This analysis modeled the stress at the front spar wing attach fitting of a subsonic Cessna A-37 Dragonfly using:

1. I-DEAS® FE Analysis model
2. JUMP® response surface metamodel
3. Excel® flight spectrum stepped approximation

The purpose of this structural modeling was to estimate crack growth propagation at the front spar wing attach fitting FCL to facilitate an ISHMS benefit analysis.

The stress intensity range, ΔK, was based on the stress amplitude, $\Delta\sigma$, the boundary condition factor, $f(g)$, and the crack length, a. The stress amplitude, $\Delta\sigma$, was the difference between the maximum and minimum stress (Figure 3.15).

Minimum stress, σ_{min}, was assumed as the unloaded wing configuration i.e., σ_{min}=0. The aircraft flight load was assumed as SLUF. The goal was to predict the maximum stress, σ_{max}, from the SLUF and weapon loading configurations. The difference in the two stresses was the stress amplitude used to calculate the crack growth rate and cycles until failure, N_f. The maximum stress, σ_{max}, on the wing was determined by the weight/location of the weapons and the lift load.

4.8 Design Goals

The design variables were defined as the amount of weapon and fuel force (lbf) loaded at each of the four pylon locations and wing tip (x_1, x_2, x_3, x_4, & x_5) (Figure 3.16). Note: the location of the weapon pylons were fixed and could not be changed, only the amount of loading at each pylon location was changed.

The cost function was the aircraft stress (psi) at the wing root spar connection to the front spar carry-through frame (wing attach fitting) element 2815 (Figure 3.17). Typical Vietnam era weapon and fuel load-out was 2501 lbs.

4.9 Problem Formulation

Once a typical A-37 weapon load was determined the development of the cost function was broken down into six stages and four parts:

1. The first stage consisted of researching the Cessna A-37 Dragonfly to gain an understanding of the structure and forces at work.
2. The second stage was making engineering assumptions to simplify the complex A-37 system into a structural simulation model.
3. The third stage was distilling the simulation model down into a response surface regression metamodel to estimate the stress experienced at the wing attach fitting.
4. The fourth stage created a stepped approximation of a fighter flight spectrum to determine mission effects on the stress at the wing attach fitting.

5. The fifth stage was feeding the stress amplitude per 100 cycles per flight hour into the MATLAB® crack growth model to estimate crack growth at the FCL over time.
6. The sixth stage was using the crack growth model to conduct a benefit analysis (Figure 3.7).

4.9.1 Four Parts of Structural Model. The four parts to successfully execute the structural model were:

1. Constructed a structural simulation model of the Cessna A-37 Dragonfly
   - Created a simulation model of the wing using FE analysis
   - Used adaptive meshing to decrease element size until max stress converged
2. Constructed a CCD for the response surface
   - Generated orthogonal fractional factorial design to minimize confounding
   - Determined design factor input ranges
3. Executed each of the I-DEAS® FE simulation runs
   - Executed required simulations from the fractional factorial design
   - Validated the simulation model results using hand calculations
4. Created a response surface regression metamodel of the FE simulation model
   - Conducted sensitivity analysis to determine loading trends on stress
   - Estimated stress at wing attach fitting using typical Vietnam weapon load-out
5. Constructed stepped approximation of fighter flight spectrum
   - Simplified flight spectrum for crack growth model
   - Estimated mission effect on wing attach fitting stress per flight hour cycle

4.10 Solution Approach

4.10.1 Modeling Issues and Simplifying Assumptions. This analysis modeled the right wing of the Cessna A-37 Dragonfly (i.e. half-wing model) (Figure 4.24) and consisted of a linear static maximum stress analysis. The flight spectrum was truncated into a stepped approximation and distilled into a weighted average effect on the wing attach fitting stress per flight hour cycle.

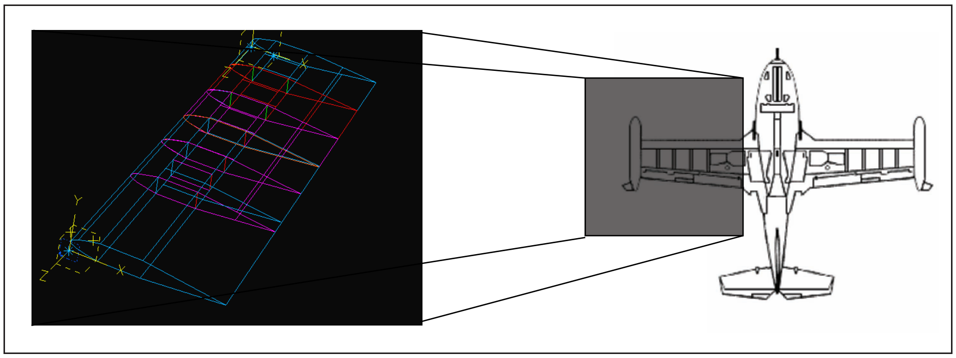

Figure 4.24: A-37 Right Wing: Half-wing Model

The structural components modeled consisted of: two spars, the wing root and tip ribs, and the aircraft skin (Figure 4.25). The spars were modeled without spar caps and the stringers and landing gear were ignored for simplicity. The airfoil geometry was a (NACA) 2418 with a chord length of 67 in at the wing root and 52.8 in at the wing tip. The span of the wing was 158 in with a 3° dihedral and a 3° counter clockwise twist [44].

The spars, skin, and ribs were modeled with 7075-T6 aluminum FE shell meshes of thickness (1 in, 0.25 in, and 1 in respectively) (Figure 4.26). These material and thickness selections where accurate for the spars and ribs, but an assumption for the wing skin.

The interior ribs were only used as weapon pylon reference points to attach weapon point loads. Weapon pylon locations consisted of the five rib locations farthest from the fuselage (to include the wing tip) (Figure 3.16).

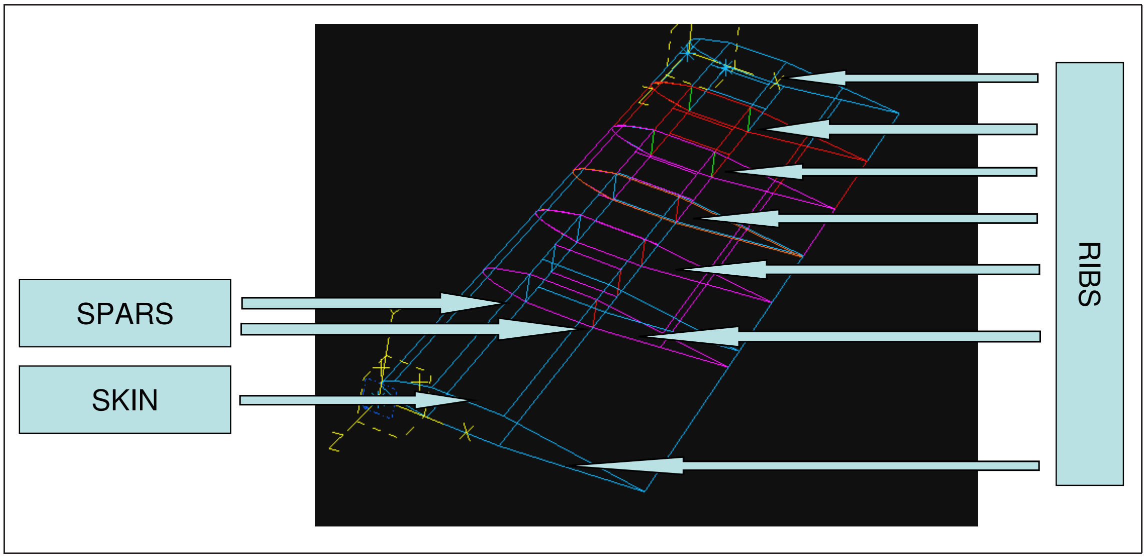

Figure 4.25: A-37 Right Wing

4.10.2 Loading Conditions. The loading conditions consisted of distributed and point loads (Figure 4.27).

The point weapon loads were divided between the front and rear spars at each of the five rib locations nearest the wing tip. The total force (SLUF assumption) of each weapon load (from the wing root outward) was: 870 lb, 870 lb, 600 lb, 500 lb, and 817 lb. The lift load pressure distribution surface along the chord from leading edge to trailing edge was calculated using DesignFoil®, a subsonic simulation program utilizing NACA airfoil and aircraft performance data (Figure 4.28). Elliptical equations for the chord pressure distribution were solved via Mathematica® and manually iterated until they approximated the DesignFOIL® data surface.

The lift load pressure distribution surface along the span from wing tip to wing root was approximated with normalized elliptical equations. The span elliptical pressure distribution equations were also solved in Mathematica® (Figure 4.29).

The chord distributed pressure surface and span distributed pressure surface were multiplied together to create a single pressure surface that would describe the distributed pressure surface on the wing (Equation 4.1).

Density	2.81 g/cc	0.102 lb/in^3
Mechanical Properties		
Hardness, Brinell	150	150
Hardness, Knoop	191	191
Hardness, Rockwell A	53.5	53.5
Hardness, Rockwell B	87	87
Hardness, Vickers	175	175
Ultimate Tensile Strength	572 MPa	83000 psi
Tensile Yield Strength	503 MPa	73000 psi
Elongation at Break	11 %	11 %
Elongation at Break	11 %	11 %
Modulus of Elasticity	71.7 GPa	10400 ksi
Poisson's Ratio	0.33	0.33
Fatigue Strength	159 MPa	23000 psi
Fracture Toughness	20 MPa-m½	18.2 ksi-in½
Fracture Toughness	25 MPa-m½	22.8 ksi-in½
Fracture Toughness	29 MPa-m½	26.4 ksi-in½
Machinability	70 %	70 %
Shear Modulus	26.9 GPa	3900 ksi
Shear Strength	331 MPa	48000 psi

Figure 4.26: 7075-T6 Aluminum Properties [9]

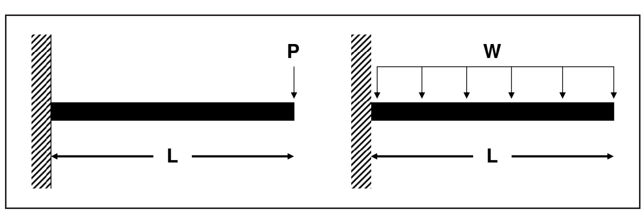

Figure 4.27: Cantilever Beam Loading Conditions [19]

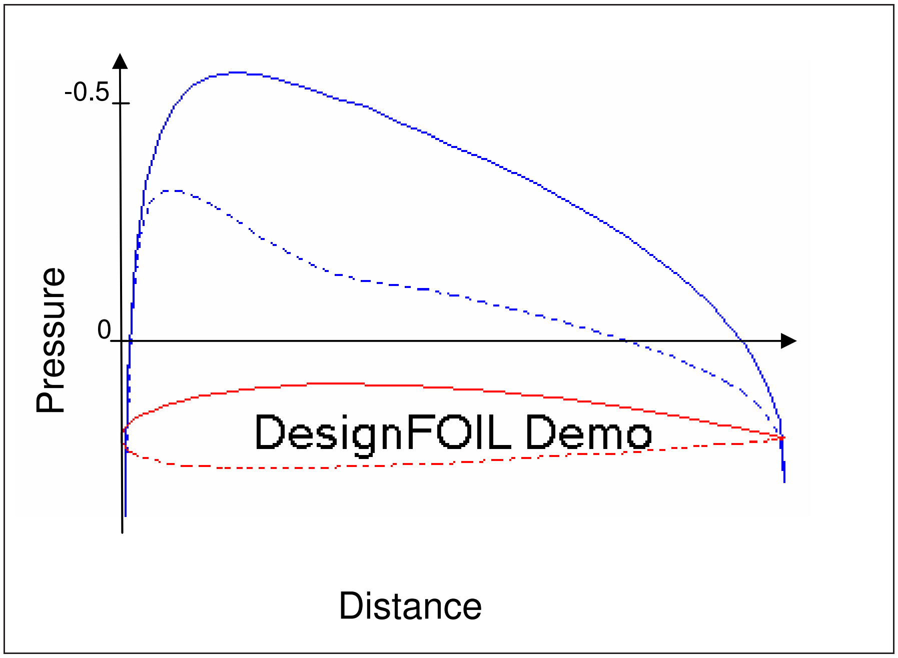

Figure 4.28: NACA 2418 Chord Lift Pressure Distribution [44]

$$L(z) \cdot L(x) = 0.00805848 \cdot \sqrt{\frac{1 - Z^2}{158^2}} \cdot \left(\left(\frac{(-0.15328 + 0.030656) \cdot X}{16.31} \right) + 0.15328 \right) \tag{4.1}$$

This single distributed pressure surface equation was applied over the wing box in conjunction with the SLUF lift pressure load of 0.656 psi (i.e. 6211 lbs of aircraft empty weight divided by 9464.2 in^2 wing box surface area) to simulate the lift loading on the A-37 wing in flight (Figure 4.30).

4.10.3 Constraints (Boundary Conditions).

1. The A-37 half-wing simulation model was constrained as a cantilever beam (i.e. Fixed-Free) with all displacements and rotations at the wing root set to zero (Figure 4.31).
2. The element size reduces the accuracy of the max stress. The original coarse FE mesh was iterated (twice) until the max stress approached a constant maximum stress value (Figure 4.32).
3. Idealized: All loading, material constants, and geometry is exact

Clear[L, a, z]

L=$\int_0^{158}\left(a*\left(\left(1-\frac{z^2}{158^2}\right)^0.5\right)\right)dz$

$Solve[L == 1, a]$

124.093a

{{a→ 0.00805848}}

Clear[M, P, Q, eqns, b, c, x]

M=((-(b+c)*x)/16.31)+ b

P=$\int_0^{16.31} M dx$

$Q = \int_0^{16.31}(x*M)dx$

$eqns$ = {P ==1, Q == 16.31/4}

Solve[eqns, {b,c}]

b + 0.0613121 (-b-c) x

8.155 b - 8.155 c

44.336 b - 88.672 c

{8.155 b - 8.155 c == 1, 44.336 b - 88.672 c == 4.0775}

{{b→ $0.15328, c \to 0.030656$}}

Figure 4.29: Elliptical Pressure Distribution Calculations

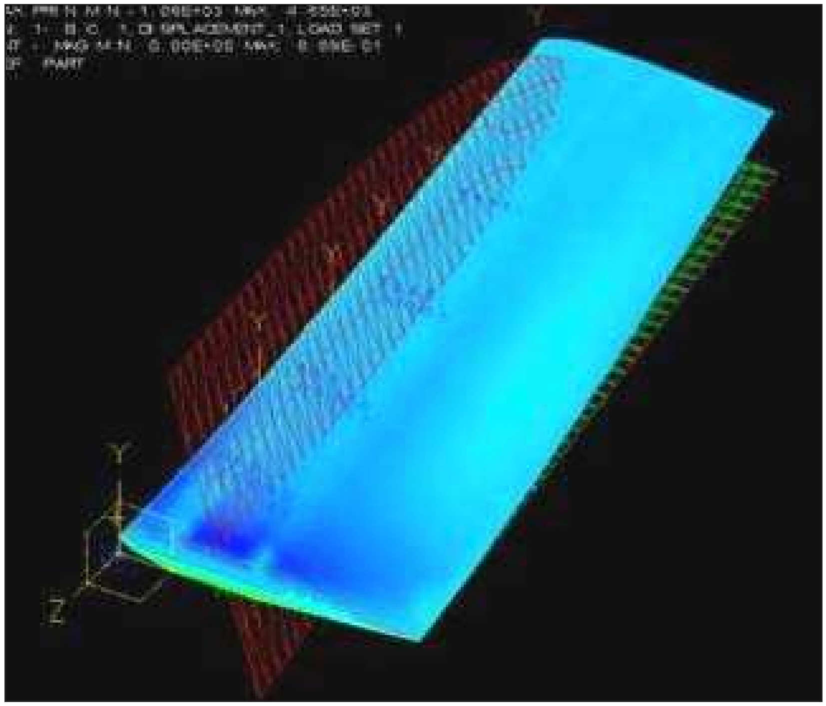

Figure 4.30: A-37 Right Wing: Typical Deformed Geometry

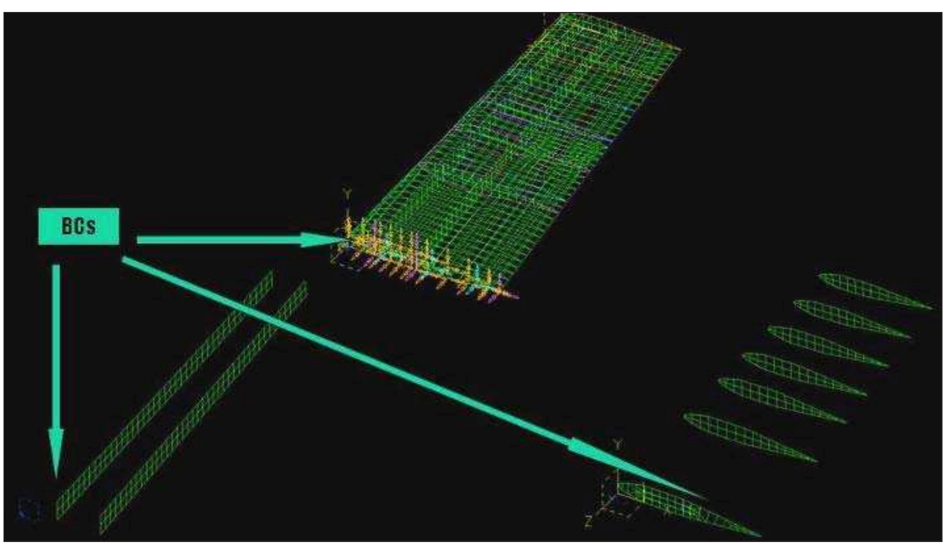

Figure 4.31: A-37 Finite Element Mesh with Cantilever Boundary Conditions

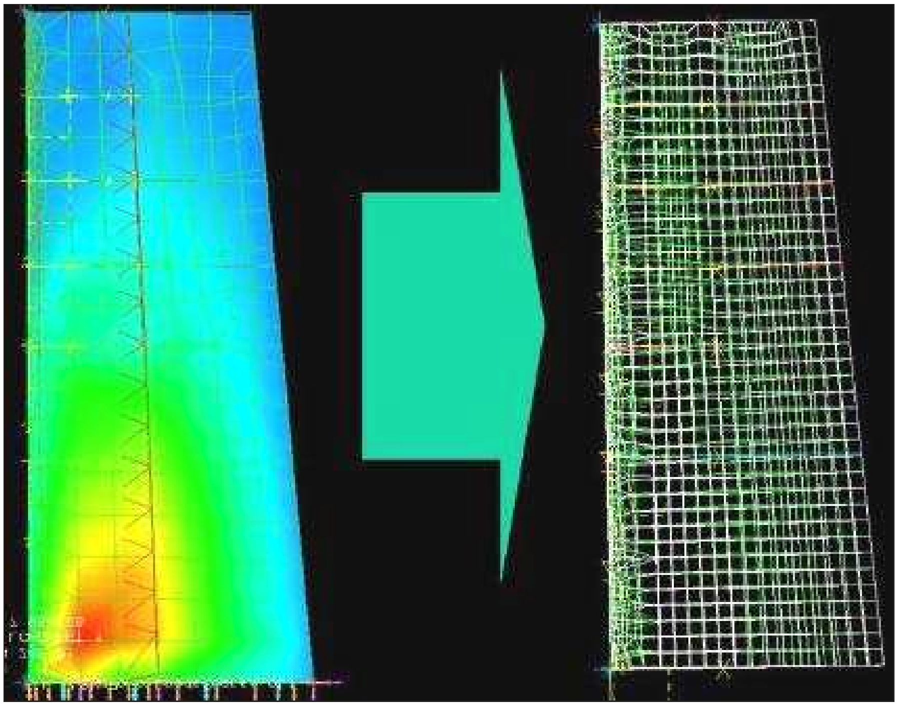

Figure 4.32: Effect of Refining A-37 Finite Element Mesh Size with Adaptive Meshing

4.10.4 Performance Measure (Criteria for Successful Structural Model Design). Maximum von Mises stress at element 2815, σ_{max}, was the performance measure and criteria for successful structural model design:

$$\sigma_{max} = \sigma_{lift} + \sigma_{weapon_{x_1}} + \sigma_{weapon_{x_2}} + \sigma_{weapon_{x_3}} + \sigma_{weapon_{x_4}} + \sigma_{weapon_{x_5}} \tag{4.2}$$

4.10.5 Constructed CCD for the Response Surface. There was a design factor (x_1, x_2, x_3, x_4, & x_5) for each of the four wing pylon loading locations and the wing tip tank location. These five factors had three levels, *1* when the pylon was loaded, *-1* when the pylon was left empty, and *0* at the midpoint (Figure 4.33).

Complete enumeration of the solution space required $3^5 = 243$ FE model simulation runs to be executed. An orthogonal $^1/_4$ fractional factorial design was chosen to

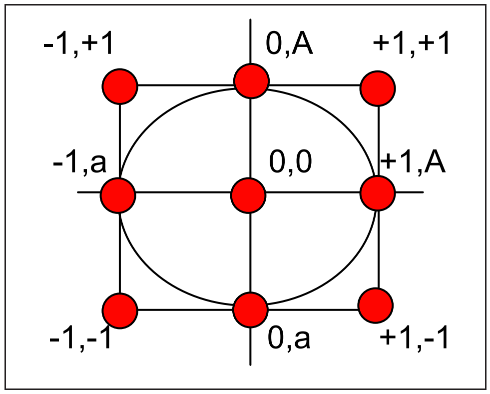

Figure 4.33: Design Factor Levels for the Central Composite Design

reduce the number of required simulation model runs to 27 (with 2 midpoints making 28) while not introducing confounding between main effects (Table 4.1).

The design factor range was the maximum allowable pylon load if the fractional factorial design was *1*, 0 if the fractional factorial design was *-1*, and half the maximum pylon load for the fractional factorial design midpoint *0*.

The A-37 FE simulation model was executed for each of the 28 fractional factorial design runs and the maximum stress results at element 2815 were tabulated. Due to the geometry of the FE model the highest stress location was consistently on the bottom edge of the front spar at the wing root (Figure 4.34).

The FE simulation model von Mises stress (psi) results were tabulated for element 2815 (Table 4.2).

4.10.6 Simulation Model Validation with Hand Calculations. Validation of the FE model required the A-37 wing to be simplified as a hollow cantilever rectangular box beam (with the two spars added back into the second moment of inertia). The beam was 158 in long, with a 52.8 in width, height of 5.82 in, and skin thickness of 0.25 in. The weapon location point loads were kept at the original magnitudes but the distributed lift load magnitude of 6211 lb was reduced to $^1/_9{}^{th}$ to simulate the effects of the two elliptical distributions on the loading and moments. The smaller outer wing tip dimensions were projected down the length of the beam to create a

Table 4.1: Central Composite Design

Simulation Number	CCD Pattern	X1	X2	X3	X4	X5
1	- - - - -	-1	-1	-1	-1	-1
2	- - - + +	-1	-1	-1	1	1
3	- - + - +	-1	-1	1	-1	1
4	- - + + -	-1	-1	1	1	-1
5	- + - - +	-1	1	-1	-1	1
6	- + - + -	-1	1	-1	1	-1
7	- + + - -	-1	1	1	-1	-1
8	- + + + +	-1	1	1	1	1
9	+ - - - +	1	-1	-1	-1	1
10	+ - - + -	1	-1	-1	1	-1
11	+ - + - -	1	-1	1	-1	-1
12	+ - + + +	1	-1	1	1	1
13	+ + - - -	1	1	-1	-1	-1
14	+ + - + +	1	1	-1	1	1
15	+ + + - +	1	1	1	-1	1
16	+ + + + -	1	1	1	1	-1
17	a 0 0 0 0	-1	0	0	0	0
18	A 0 0 0 0	1	0	0	0	0
19	0 a 0 0 0	0	-1	0	0	0
20	0 A 0 0 0	0	1	0	0	0
21	0 0 a 0 0	0	0	-1	0	0
22	0 0 A 0 0	0	0	1	0	0
23	0 0 0 a 0	0	0	0	-1	0
24	0 0 0 A 0	0	0	0	1	0
25	0 0 0 0 a	0	0	0	0	-1
26	0 0 0 0 A	0	0	0	0	1
27	0 0 0 0 0	0	0	0	0	0
28	0 0 0 0 0	0	0	0	0	0

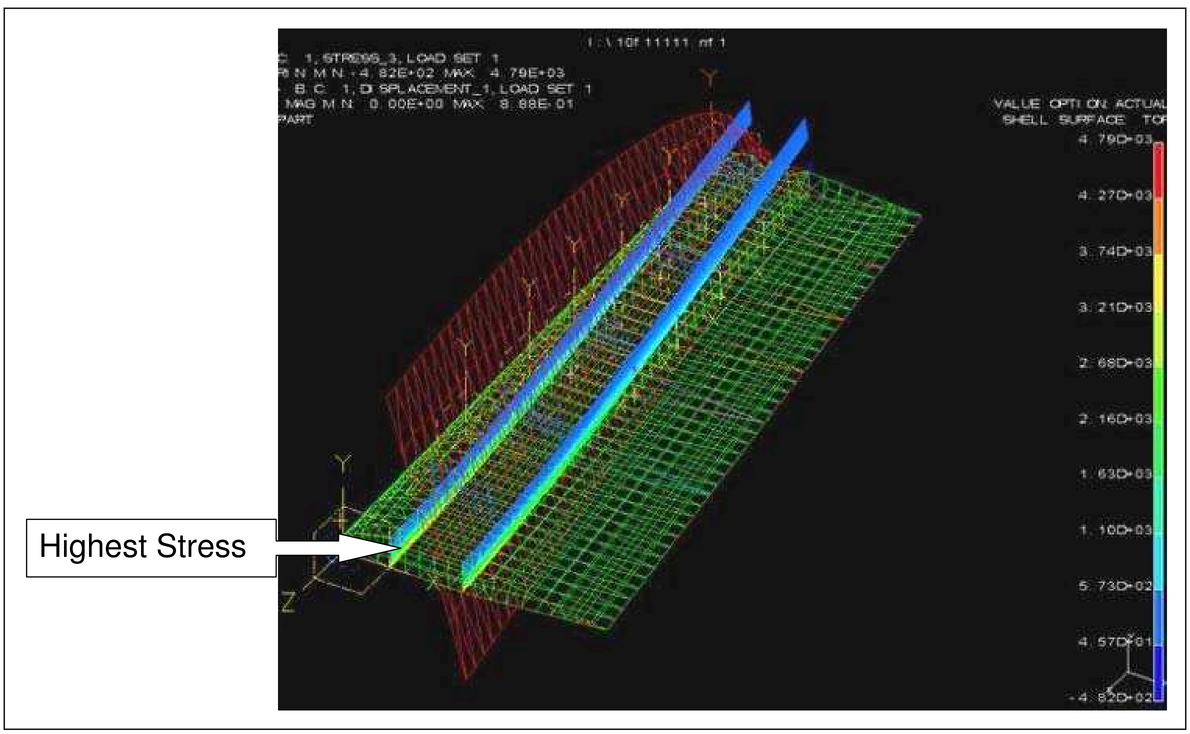

Figure 4.34: Max Stress on Bottom Edge of Front Spar

Table 4.2: Central Composite Design Results

Simulation Number	CCD Pattern	X1	X2	X3	X4	X5	Y
1	- - - - -	-1	-1	-1	-1	-1	2907
2	- - - + +	-1	-1	-1	1	1	4569
3	- - + - +	-1	-1	1	-1	1	3679
4	- - + + -	-1	-1	1	1	-1	1805
5	- + - - +	-1	1	-1	-1	1	2765
6	- + - + -	-1	1	-1	1	-1	1993
7	- + + - -	-1	1	1	-1	-1	2018
8	- + + + +	-1	1	1	1	1	4569
9	+ - - - +	1	-1	-1	-1	1	2515
10	+ - - + -	1	-1	-1	1	-1	1773
11	+ - + - -	1	-1	1	-1	-1	3459
12	+ - + + +	1	-1	1	1	1	4348
13	+ + - - -	1	1	-1	-1	-1	1986
14	+ + - + +	1	1	-1	1	1	4536
15	+ + + - +	1	1	1	-1	1	4561
16	+ + + + -	1	1	1	1	-1	3789
17	a 0 0 0 0	-1	0	0	0	0	2285
18	A 0 0 0 0	1	0	0	0	0	3167
19	0 a 0 0 0	0	-1	0	0	0	2175
20	0 A 0 0 0	0	1	0	0	0	3277
21	0 0 a 0 0	0	0	-1	0	0	2269
22	0 0 A 0 0	0	0	1	0	0	3183
23	0 0 0 a 0	0	0	0	-1	0	2281
24	0 0 0 A 0	0	0	0	1	0	3171
25	0 0 0 0 a	0	0	0	0	-1	1895
26	0 0 0 0 A	0	0	0	0	1	3557
27	0 0 0 0 0	0	0	0	0	0	2726
28	0 0 0 0 0	0	0	0	0	0	2726

smaller simplified wing that sets a maximum possible stress that cannot be exceeded with a valid model (Figure 4.35).

It was a good sign that the maximum stress achieved in the fully loaded simulation model did not exceed the maximum theoretical stress. Additionally, the maximum stress achieved in the simulation model was within a power of 10 of the maximum theoretical stress so there was confidence that the FE simulation model was valid.

4.10.7 Response Surface Regression Metamodel.

- The original A-37 simulation model boundaries were identified.
- The weapon pylon factors (x_1, x_2, x_3, x_4, & x_5) contributing to the simulation model were identified and the range of the factors (0 to maximum pylon load rating) was established.
- CCD Fractional factorial design was used to cut down the number of simulation runs. Each of the 5 factors had 3 levels (high, mid, and low value) so the number of simulation model runs required was 3^5. Conducting 243 runs would have been time consuming so a fractional $^1/_4$ factorial design was used to reduce the number of runs to 28 (27 + 1 additional midpoint).
- The max von Mises stress FE simulation model was solved in I-DEAS® for the CCD factor configurations.
- The form of the A-37 response surface regression model was established as a quadratic regression to include main effects, quadratic terms, and two factor interactions (Equation 4.3 [64]).

$$\begin{aligned} Y_i = \beta_0 + \sum_{h=1}^{k} \beta_h x_{ih} + \sum_{h=1}^{k} \beta_{hh} x_{ih}^2 \\ + \sum_{h=1}^{k-1} \sum_{h'=h+1}^{k} \beta_{hh'} x_{ih} x_{ih'} + E_i, \forall i = 1, ..., n \end{aligned} \tag{4.3}$$

Hand Calculations for Simulation Model Validation							
	Point Load					Distributed Load	
	X5	X4	X3	X2	X1		
width inner (in)	52.30	52.30	52.30	52.30	52.30	width inner (in)	52.30
height inner (in)	5.82	5.82	5.82	5.82	5.82	height inner (in)	5.82
width outer (in)	52.80	52.80	52.80	52.80	52.80	width outer (in)	52.80
height (in)	6.32	6.32	6.32	6.32	6.32	height (in)	6.32
spar width (in)	1.00	1.00	1.00	1.00	1.00	spar width (in)	1.00
spar height (in)	5.82	5.82	5.82	5.82	5.82	spar height (in)	5.82
I Moment of Inertia (in^4)	32.86	32.86	32.86	32.86	32.86	I Moment of Inertia (in^4)	32.86
W, Load (lbf)	817.00	500.00	600.00	870.00	870.00	W, Load (lbf)	676.38
E (psi)	10,400,000.00	10,400,000.00	10,400,000.00	10,400,000.00	10,400,000.00	E (psi)	10,400,000.00
L, Distance (in)	158.00	138.00	118.00	98.00	79.00	L, Distance (in)	158.00
y (in)	3.16	3.16	3.16	3.16	3.16	y (in)	3.16
Point Load Stress (psi)	12,413.08	6,635.13	6,808.22	8,198.72	6,609.17	Distributed Load Stress (psi)	3,425.51
						MAX Theoretical Stress (psi)	44,089.84
						MAX Stress Achieved (psi)	4790.00

Figure 4.35: Maximum Stress Hand Calculations

The response surface regression metamodel was calculated with a R^2 value of 0.970 indicating a metamodel that accounts for the vast majority of the factors that are influencing the max stress on element 2815 of the A-37 wing (Figure 4.36).

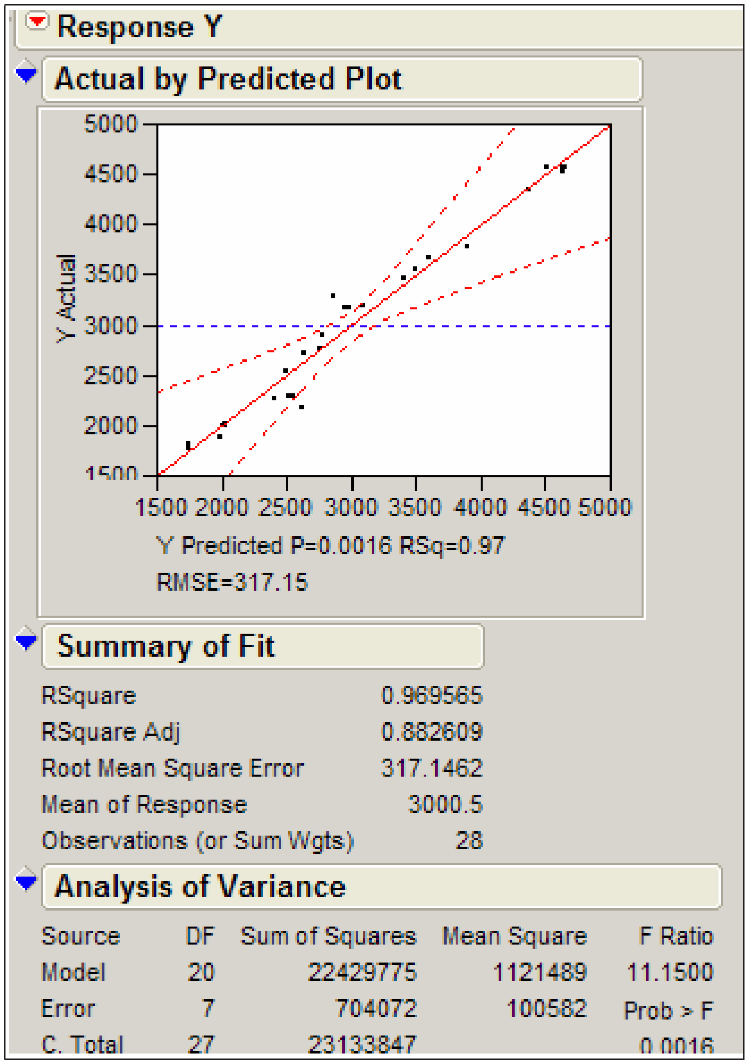

Figure 4.36: Regression Metamodel Results

Only parameter estimates with an F-ratio greater than one were included as significant in the response surface metamodel (Table 4.3).

This inclusion of significant factors resulted in a response surface model (Equation 4.4 [64]). Even though the quadratic effects were included in the response surface model, the F-ratios show that these second order terms were not as significant as the first order and two-factor interactions.

Table 4.3: Regression Parameter Estimates

Term	**Estimate**	**F-Ratio**	**Probability>t**
Intercept	2635.04	23.86	<0.0001
X1&RS	198.56	2.66	0.0326
X2&RS	124.11	1.66	0.1408
X3&RS	337.11	4.51	0.0028
X4&RS	241.78	3.23	0.0144
X5&RS	750.22	10.04	<0.0001
X1*X2	272.63	3.44	0.0109
X1*X3	342.5	4.32	0.0035
X2*X3	135	1.7	0.1324
X1*X4	20.5	0.26	0.8034
X2*X4	228.25	2.88	0.0237
X3*X4	-117.13	-1.48	0.1831
X1*X5	-117.25	-1.48	0.1827
X2*X5	90.5	1.14	0.2912
X3*X5	20.63	0.26	0.8022
X4*X5	342.63	4.32	0.0035
X1*X1	113.7	0.56	0.5923
X2*X2	113.7	0.56	0.5923
X3*X3	113.7	0.56	0.5923
X4*X4	113.7	0.56	0.5923
X5*X5	113.7	0.56	0.5923

$$\begin{aligned}\sigma = 2635 &+ 199x_1 + 124x_2 + 337x_3 + 242x_4 + 750x_5 \\ &+273x_1x_2 + 343x_1x_3 + 135x_2x_3 + 228x_2x_4 \\ &-117x_3x_4 + 91x_2x_5 + 343x_4x_5\end{aligned} \tag{4.4}$$

4.10.8 Sensitivity Analysis. A sensitivity analysis was performed on the response surface model (Equation 4.5). The sensitivities were calculated to determine which factor had the greatest effect on the stress induced in the aircraft wing attach fitting (element 2815).

$$
\begin{aligned}
\frac{\partial \sigma}{\partial x_1} &= 199 + 273x_2 + 343x_3 - 117x_5 \\
\frac{\partial \sigma}{\partial x_2} &= 124 + 273x_1 + 135x_3 + 228x_4 + 91x_5 \\
\frac{\partial \sigma}{\partial x_3} &= 337 + 343x_1 + 135x_2 - 117x_4 \\
\frac{\partial \sigma}{\partial x_4} &= 242 + 228x_2 - 117x_3 + 343x_5 \\
\frac{\partial \sigma}{\partial x_5} &= 750 - 117x_1 + 91x_2 + 343x_4
\end{aligned} \tag{4.5}
$$

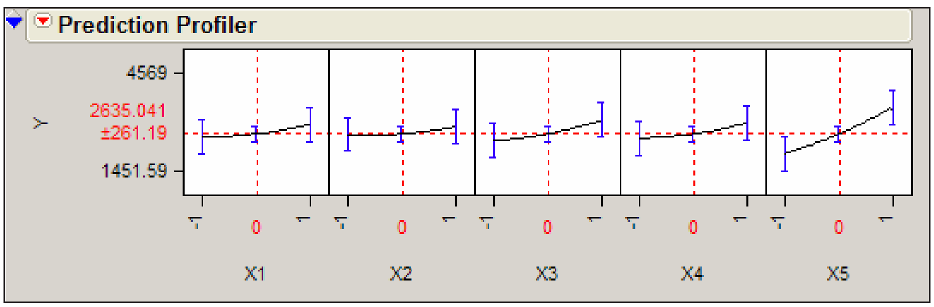

Figure 4.37: Regression Graphical Sensitivity

4.10.9 Fighter Flight Spectrum.

4.10.9.1 Stress Sequence Development. The sequence and intensity of stress cycles applied during the life of the aircraft structure was needed to estimate crack growth at the wing attach fitting FCL. This flight spectrum was usually recorded as gravitational loads per flight hour cycle (Figure 4.38).

This spectrum was a general fighter repeated load history due to ground handling, flight maneuvers, gusts, landing, store ejection, and other load sources. A-37 data was not available, so this general fighter spectrum was used to estimate the effect on stress per flight hour cycle [66]. The stress effect at any given flight hour cycle was determined from the spectrum load & stress relationship [47]. Each aircraft mission type was divided into segments which were characterized by the type and

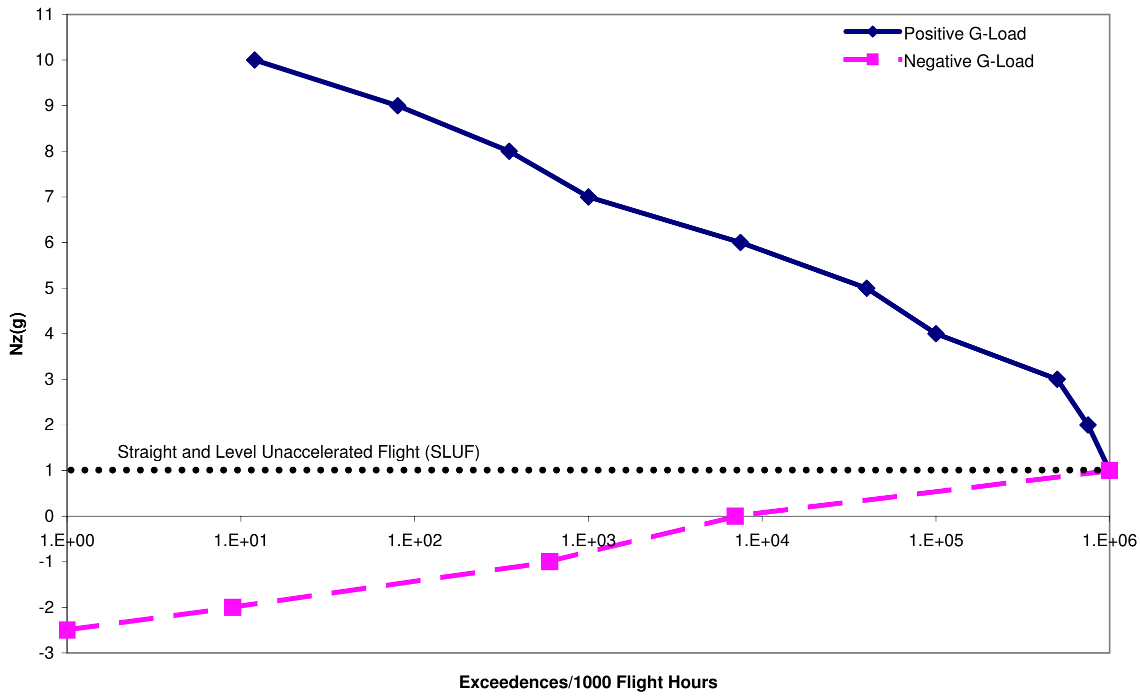

Figure 4.38: General Fighter Flight Spectrum [66]

frequency of load sources (Figure 4.39 [66]). Multiple mission profiles and segments were combined to determine the flight spectrum. Specifically, the flight spectrum was constructed from aircraft service life data. Flight hours, calendar years of service, number of missions flown, mission types, and number of landings were included in service life data.

The flight maneuver spectrum was determined by summing the number of times the gravitational load factors (g-loads) were exceeded per flight hour cycle. The g-loads were converted to percent of limit load (stress) (Figure 4.40).

The number of exceedances were truncated logarithmically. The stresses and cycles were distributed among A-D decreasing severity mission profiles (Table 4.4). The stresses generated per flight hour cycle were combined in a weighted average for simplification of the crack growth model and inserted into the benefit analysis.

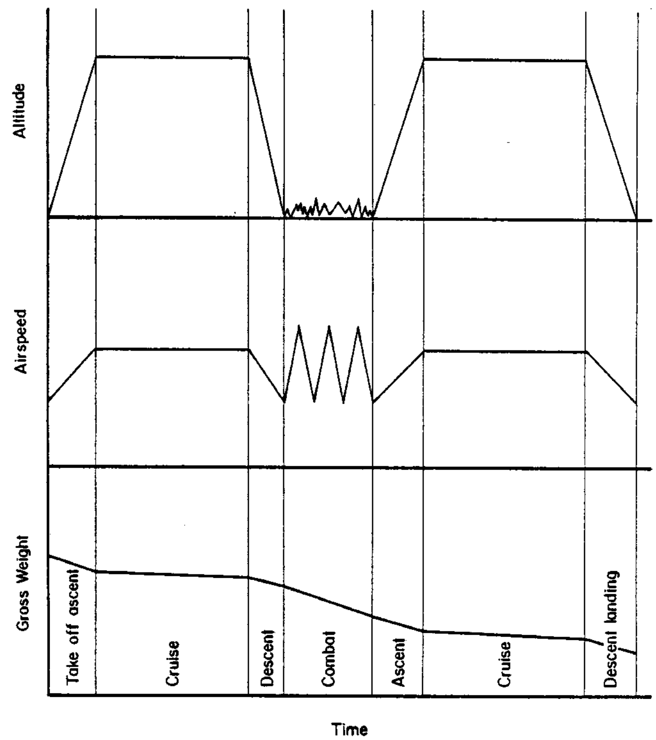

Figure 4.39: General Aircraft Mission Profile [66]

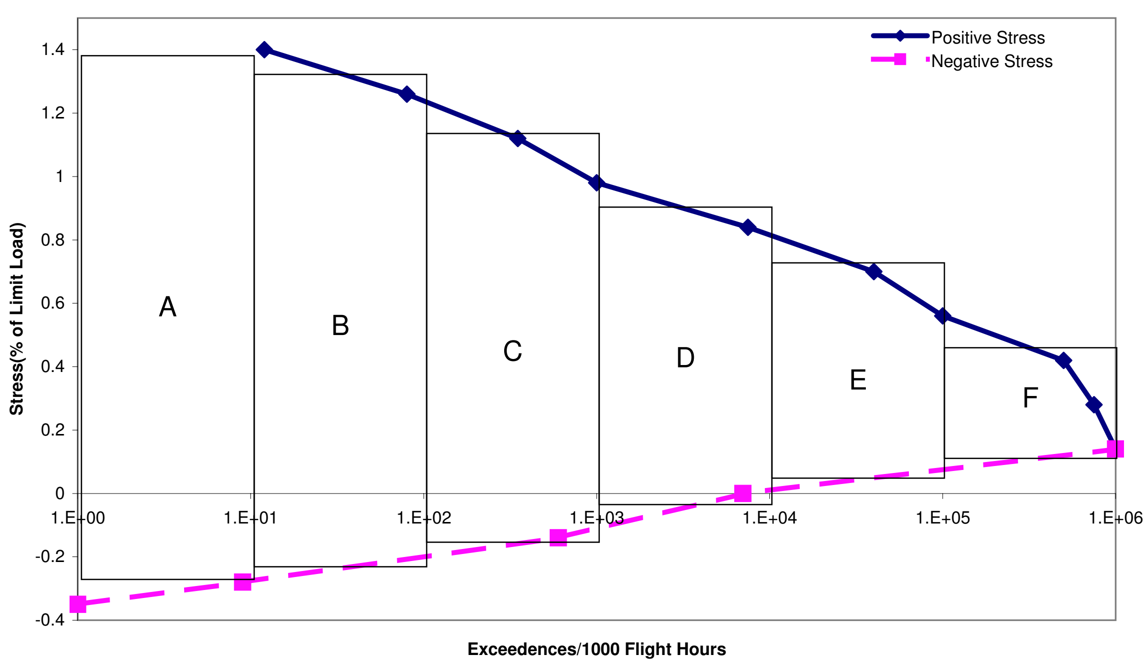

Figure 4.40: Flight Stress Sequence Stepped Approximation [66]

Table 4.4: Stress and Cycle Distribution

Composite		
1 (Level)	**2 (Exceedances)**	**3 (Occurrences)**
1.39	10	10
1.35	100	90
1.15	1000	900
0.9	10000	9000
0.75	100000	90000
0.52	500000	400000
Mission A		
4 (Occurrences)	**5 (10x)**	**6 (Remain=3-5)**
1	10	0
3	30	60
15	150	750
48	480	8520
300	3000	87000
1900	19000	381000
Mission B		
7 (Occurrences)	**8 (60x)**	**9 (Remain=6-8)**
0	0	0
1	60	0
3	180	570
17	1020	7500
200	12000	75000
1500	90000	291000
Mission C		
10 (Occurrences)	**11 (570x)**	**12 (Remain=9-11)**
0	0	0
0	0	0
1	570	0
10	5700	1800
100	57000	18000
400	228000	63000
Mission D		
13 (Occurrences)	**14 (360x)**	**15 (Remain=12-14)**
0	0	0
0	0	0
0	0	0
5	1800	0
50	18000	0
175	63000	0

4.11 Structural Model Discussion of Results and Summary

Simulation and response surface modeling worked well. The FE simulation correlated reasonably well to the hand calculations. This analysis showed that weapon loading correlates highly with wing attach fitting stress. The wing pylon location that had the most detrimental effect on the A-37 maximum wing stress is the wing tip tank location (x_5). The stress sensitivities showed an increasing significance of x_5 on the induced stress of the wing root front spar (element 2815). Additionally, the sensitivity analysis shows that the optimum loading configuration is to put the heaviest weapons on the inner pylons first. Following these weapon pylon loading guidelines resulted in a maximum von Mises stress, smax, of 4790 psi at the wing attach fitting element 2815. The effect of applying the flight maneuver spectrum was significant. The limit load for fighter aircraft was 7.33g which resulted in a weighted stress of 20,152 psi for 100 cycles per flight hour. This was the stress per cycle values input into the Walker crack growth model for the benefit analysis.

The results of the benefit analysis are presented in the following section. The benefit analysis is composed of a structural model that feeds into both a baseline 300 hour simulation and ISHMS modified simulation.

4.12 Benefit Analysis

As written in Chapter 3, two MATLAB® simulations were performed to gain a rudimentary analysis of the benefit of an installed ISHMS with respect to both safety and cost. The results of running these two simulations while varying the interval between maintenance inspections are presented in this section. For reference, the MATLAB® code for the two simulations is included in Appendix A.

4.12.1 Baseline Simulation. Currently, CAF A-37 aircraft flown past the design service life are subject to maintenance inspections every 300 flight hours. The baseline simulation simulating the current status quo was run with inspection interval times of 100, 200, 300, 400, 500, 600 and 700 flight hours. The 700 hour interval

Table 4.5: Baseline Simulation Results

Run	Inspect Interval (Flight Hrs)	Fleet Failures Average	Fleet Failures Std Dev	Failure Rate (per Mln Flt Hrs)	Total Failures	Max Fleet Failures	Total Inspects
1	100	0	0	0	0	0	650000
2	200	0.007	0.0834	0.1077	7	1	324932
3	300	0.159	0.3998	2.4593	159	3	206912
4	400	3.721	1.5785	66.6713	3721	8	132434
5	500	3.126	1.5161	54.5228	3126	8	113650
6	600	2.767	1.4632	47.3156	2767	10	93769
7	700	13.0	0	1626	13000	13	90666

resulted in every aircraft failing prior to scheduled inspection. Any interval greater than 700 hours will also result in every aircraft failing prior to inspection, thus the simulations were not performed at intervals greater than 700 flight hours. The results of these seven runs are presented in Table 4.5. These baseline runs helped to characterize the baseline behavior such that it could be compared with the ISHMS simulation.

The results showed that the failure rate for the 300 hour inspection is 2.4593 failures per million flight hours. This exceeded the current acceptable USAF goal of one failure per million flight hours. The maximum fleet failures was three which would amount to 23% of the fleet failing during the 5000 flight hour life; this occurred in 0.001% of the trials. Additionally, results showed that the failure rate increased dramatically between 300 and 400 hour inspection intervals. At intervals greater than 400 hours, the failure rate dropped some before hitting a peak when all aircraft failed at 616 hours.

Since the crack growth was deterministically estimated and would reach the critical length at 615 flight hours, any inspection interval beyond 615 flight hours for the baseline resulted in failures for all aircraft. The drop observed from 400 flight hours to 615 flight hours can be attributed to the probability of maintenance detection. After each maintenance inspection, roughly three percent of the cracks do not get repaired and continue growing. At inspection intervals greater than 308 flight hours (half the time until critical crack length), these *missed* cracks will certainly fail before the next inspection. Since the total time considered by the model was limited to 5000 flight hours, the total number of *missed* cracks will decrease as the inspection

interval increases from 400 to 616 flight hours. For example, at 600 flight hours there will be fewer total inspections and fewer opportunities to miss cracks than at 400 flight hours. This results in fewer failures for the 600 flight hour interval as compared to the 400 flight hour interval. See Figure 4.41 for a plot of failure rate versus inspection interval.

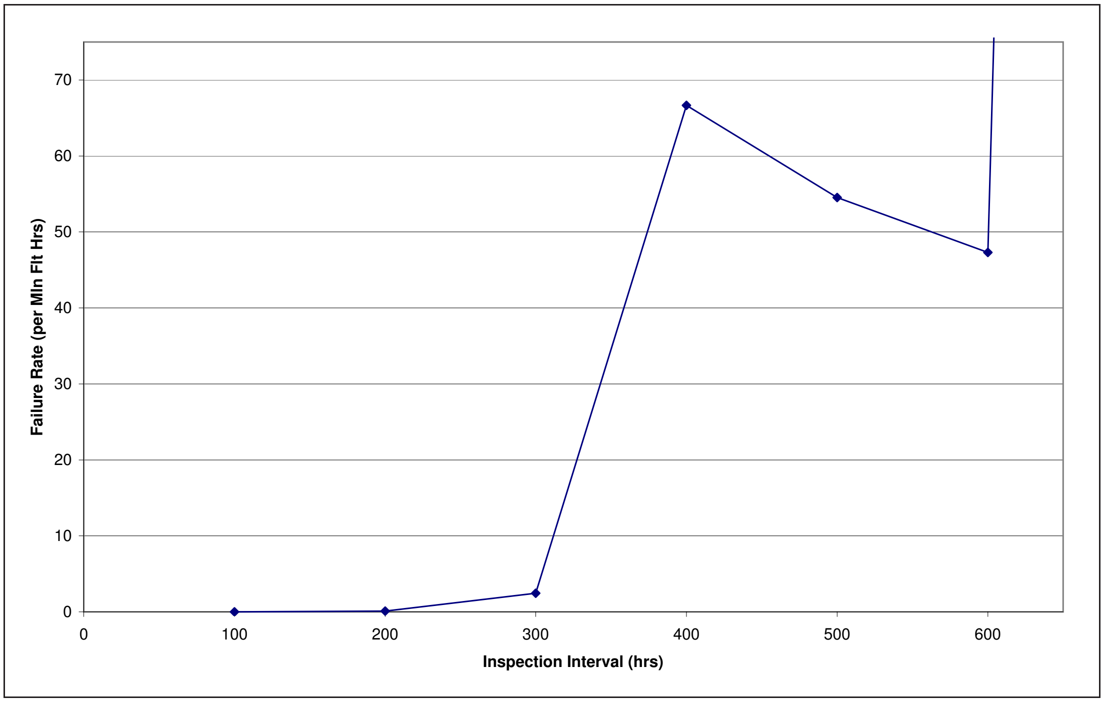

Figure 4.41: Baseline Simulation Failure Rate vs. Inspection Interval

Along with the failure rate, the standard deviation increased significantly between 300 and 400 hours, then decreased some until 615 flight hours when all aircraft failed and standard deviation was zero. As expected, total number of inspections decreased when inspection interval increased, due to a combination of the increased inspection interval and the increased number of failures.

4.12.2 ISHMS Simulation. Since it would not be desirable to decrease the inspection interval from a cost standpoint, the thesis team began our simulations for the ISHMS at 300 flight hour intervals, the current inspection interval. The thesis team then increased the interval until every aircraft failed or until the scheduled

Table 4.6: ISHMS Simulation Results

Run	Inspect Interval (Flight Hrs)	Fleet Failures Average	Fleet Failures Std Dev	Failure Rate (per Mln Flt Hrs)	Total Failures	Max Fleet Failures	Total Inspects
1	300	0	0	0	0	0	208164
2	400	0.004	0.0632	0.0615	4	1	156840
3	500	0.001	0.0316	0.0154	1	1	130406
4	600	0.017	0.1293	0.2618	17	1	106595
5	700	0.107	0.325	1.6522	107	2	103525
6	800	0.103	0.3201	1.59	103	2	103555
7	900	0.094	0.3054	1.4509	94	2	103576
8	1000	0.106	0.3207	1.6373	106	2	103490
9	1100	0.105	0.3195	1.6211	105	2	103542
10	none	0.105	0.3195	1.6215	105	2	103514

inspection interval was greater than the remaining aircraft life. The latter ending up being the case for this simulation; the only inspections performed during run 10 were when the ISHMS indicated a crack length greater than 90% of the critical length. For different runs, the thesis team increased the inspection interval by 100 hours until the failure rate exceeded the failure rate for the baseline simulation at 300 hours. This never occurred, even with *zero* scheduled inspections the failure rate was 1.6215 failures per million flight hours. The ISHMS simulation was run with inspection interval times of 300, 400, 500, 600, 700, 800, 900, 1000, 1100 and none. The results of these 10 runs can be seen in Table 4.6.

The failure rate increased dramatically between 600 and 700 scheduled inspection intervals. For inspection intervals greater than 700 flight hours, the failure rate remained fairly constant, even when relying solely on the ISHMS (i.e., zero scheduled inspections). The standard deviation of the total failures also remained constant during those same simulation runs. Never did the maximum number of fleet failures exceed two. When it did, it never occurred in more than 0.003% of the trials. The total number of inspections which included both scheduled and unscheduled (i.e., tipped off by the ISHMS) decreased from the 300 to the 500 flight hour interval, but then remained relatively constant thereafter. See Figure 4.42 for a plot of the failure rate versus inspection interval with a trendline added.

A hypothesis on the reason for the leveling off above 500 flight hours is that the crack grows to near critical length at 615 flight hours and, at that time if the scheduled inspections do not *catch* it then the unscheduled ISHMS induced inspections will,

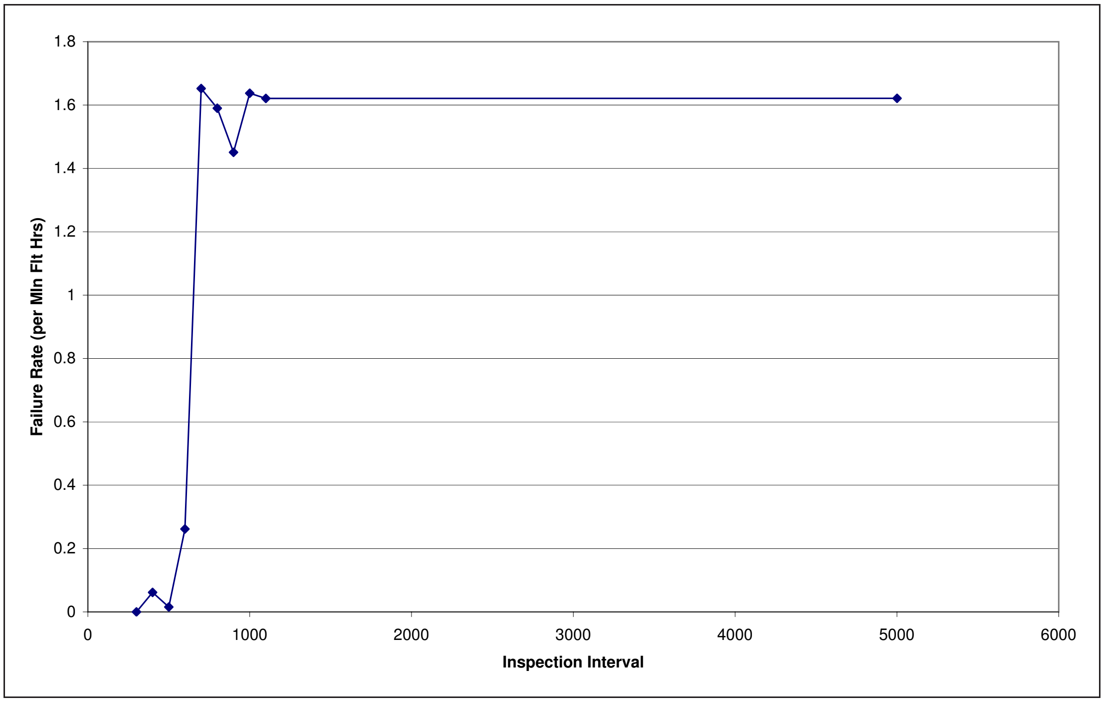

Figure 4.42: ISHMS Simulation Failure Rate vs. Inspection Interval

resulting in an inspection interval for both scheduled and unscheduled inspections to be relatively constant despite the scheduled inspection interval.

4.12.3 Discussion of Results. The simulations had many simplifying assumptions, however, since many of the assumptions were constant through the two scenarios, the thesis team believe some basic conclusions can be made. Installing a structural health monitoring system that provides real-time monitoring and feedback will most definitely improve safety for a given scheduled inspection interval. Considering the 300 flight hour inspection interval, the ISHMS reduced the failure rate from 2.4593 failures per million flight hours to zero failures. However, there was a tradeoff. The number of inspections performed with the ISHMS was slightly greater than the number of inspections for the baseline.

If an ISHMS was developed and installed, then, of course, the CAF would take advantage of this system and subsequently increase the scheduled inspection interval. Assuming 2.4593 failures per million flight hours is an acceptable failure rate then

the inspection interval with the ISHMS could eliminated. This might seem to be the course of action, but eliminating all scheduled inspections would then require that the fleet inspections, roughly 103 per fleet, would all be based on warnings from the ISHMS and thus unscheduled. Having all maintenance inspections unscheduled would not be ideal from a planning perspective. Since the failure rate for no scheduled inspections does not differ much from the 700 flight hours and greater, the optimal scheduled inspection interval with the ISHMS would be closer to 700 flight hours. With a 700 flight hour inspection interval, most of the 103 inspections per fleet would be scheduled and just a few would result from an ISHMS warning. This strikes a balance between safety, cost and planning considerations.

As an example, if the 700 flight hour inspection were selected to implement with an ISHMS installed, then the failure rate would decrease from 2.4593 failures per million flight hours to 1.6522 failures per million flight hours, a safety improvement of 32.8%. Additionally, total number of inspections would decrease from 207 to 104, a reduction of 49.8%. Assuming a fixed cost for each inspection, then the cost savings realized from installing an ISHMS system could be calculated as the fixed cost of each inspection times the number of inspections saved, 103, less the annualized life-cycle cost of an ISHMS (includes development, procurement, installation, maintenance, and disposal). The ultimate decision on changing maintenance inspections and practices would be set by the stakeholders to match their preferences and goals for the system.

4.12.4 Sensitivity Analysis. The sensitivity analysis reran the two simulations but with the maintenance probability of inspection at 98%, 99%, and 100%. For each variance in maintenance probability of inspection, the thesis team tried to find the ISHMS inspection interval that most closely matched the failure rate of the baseline with a 300 hour inspection interval, but was no worse than. For 98%, the appropriate inspection interval for the ISHMS would be approximately 600 flight hours. This would result in a safety improvement of 80.8% and a inspection reduction of 49.1%. For 99%, the appropriate inspection interval for the ISHMS would also be 600

Table 4.7: Simulation Results Summary

Maintenance Prob of Detection	Approx ISHMS Inspection Interval	Safety Improvement	Inspection Reduction
97%	700	32.8%	49.8%
98%	600	80.8%	49.1%
99%	600	50.0%	49.6%
100%	550	0%	43.8%

flight hours. This would result in a safety improvement of 50% and a inspection reduction of 49.6%. For 100%, the appropriate inspection interval for the ISHMS would be 550 flight hours. This would result in no safety improvement, since no failures occur in the baseline simulation with a 300 hour inspection interval. However, there was a inspection reduction of 43.8%. The results of the sensitivity analysis, including the original estimate of 97% for maintenance probability of detection, are included in Table 4.7.

V. Conclusions and Recommendations for Further Research

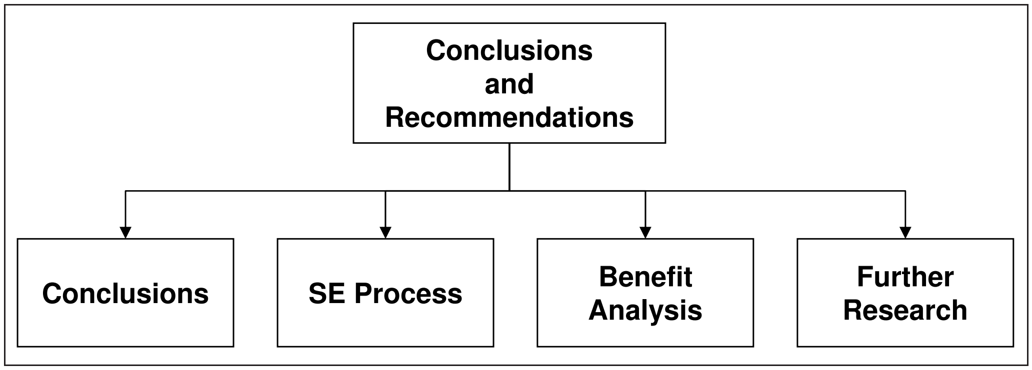

Figure 5.1: Chapter 5 Decomposition

5.1 Conclusions

As introduced in Chapter 1 and further discussed in Chapter 2, the USAF and many other nations continue to squeeze as much usable life out of aging aircraft as possible. In order to do so, the military forces regularly extend the original aircraft service life which often increases the inspection burden. To maintain flight safety, increased periodic inspections are required. Increasing the inspections results in more aircraft downtime and added maintenance costs.

This thesis first assumed that an ISHMS for aging aircraft may help lower the resulting inspection burden and, as such, reduce costs while maintaining safety. To begin to tackle the large problem of developing an ISHMS for aging aircraft, this thesis took the first steps of a generic SE process that kick started the system definition. Additionally, the potential benefit with respect to both cost and safety of an ISHMS was quantified through the use of mathematical simulations.

5.2 SE Process Developed

The problem of structural health monitoring for aging aircraft is significant and large. This thesis does not seek to solve the entire problem, especially not for specific aging aircraft. This thesis scoped the problem by focusing on the system definition

piece of the SE process for a generic aging aircraft. The authors of this thesis hope that the generic process developed will provide a starting point for future researchers of the ISHMS problem or the developers of an ISHMS for a specific aircraft. When the process required a specific aircraft for development of requirements or architectures, the CAF A-37 was used, but most of the process considered a generic aging aircraft platform. The system definition process roughly followed the SE Vee Model. The two steps of (1) defining the system level design problem and (2) developing the functional system architecture were included. Since a generic platform was considered and the thesis team consisted only of system engineers and no design engineers, the process stopped prior to physical architecture development and system design. The generic SE process detailed in this thesis included a discussion of the user perspective, definition of the operational concept, definition of user and system level requirements, requirements feasibility analysis and development of some integrated system architectures.

5.2.1 User Part of SE Process. In developing the SE process the thesis team had to wear the hats of several stakeholders. First, the thesis team played the role of the user. The user would initiate the development program for an ISHMS. This thesis assumed that the user had analyzed the alternatives for decreasing the costs associated with maintaining aging aircraft while maintaining flight safety and the user determined that an ISHMS had promise for solving the problem. When defining the operational concept, the thesis team assumed the user sought to use an ISHMS to monitor structural damage, specifically crack growth, as it occurred. As such, the health of the aircraft structure could be constantly monitored and the maintenance of the aircraft could be tailored to the individual aircraft based on the results of the monitoring. Given the assumption of an ISHMS could help solve the problem and how the user will use an ISHMS, the thesis team drafted the user requirements for an ISHMS. As stated, the user requirements considered an generic aircraft platform except when a specific platform was required. For example, when the proper sampling

rate for the ISHMS was needed, the thesis team analyzed the A-37 to determine what sampling rate was necessary to capture the peak loads.

5.2.2 System Requirements. After completing the user piece role in system definition, the thesis team changed hats and played the role of the system engineers. The user requirements and operational concept were then used to write the system requirements. The thesis team ensured requirements traceability, that the system requirements addressed each and every user requirement. As the system requirements were developed, the thesis team had to go back and clarify some user requirements. This simulated the process of the system engineers contacted the user for clarity on requirements or more detail on how the system will be used. After the system requirements were finalized, a basic feasibility check was performed ensuring that each requirement could be verified during system level design.

5.2.3 System Architectures. To further define the ISHMS and aid in clarifying the problem, the thesis team developed system architectures. The architectures developed followed the United States DoDAF. First, the AV-1, and AV-2 were created that provided textual definitions and descriptions of the problem. The OV-1 served as a graphical depiction of the operational concept. The remaining architectures developed the OV-2, OV-3 and OV-5 defined the functional processes, informational exchange and node connectivity specific to an ISHMS. Further architectural products would have delved into the physical design specifics of the ISHMS, and thus this thesis stopped the architecture development here. An interesting note, much like when developing the system requirements, development of the system architectures often identified gaps in the user and system requirements which were iteratively corrected as the architectures were created.

5.2.4 Final Comments on SE Process. This thesis was successful in developing a generic SE process for ISHMS system definition. The SE process generated a methodical, structured approach which allowed for the thesis team to effectively

define an ISHMS for a non-specific aging aircraft. The*strawman* process serves as the starting point for further system developers. After the completion of the SE process, the thesis team sought to quantify the benefit of an ISHMS on aging aircraft. In order to do so, the thesis team had to assume some system design details and created simplified simulations to compare the status quo with an ISHMS installed aircraft.

5.3 Benefit Analysis (Cost & Safety)

In the background research on structural health monitoring performed for this thesis, the potential benefit of a structural health monitoring system was not truly addressed nor quantified. Most discussion on the topic assumed the potential benefit. This thesis considered it important to attempt to quantify or show the potential benefit from both the cost and safety perspective, especially for an ISHMS on aging aircraft where installation of the ISHMS may be difficult and costly. To demonstrate the benefit of an ISHMS on aging aircraft, two simplified mathematical simulations were created, one simulating flying an aging aircraft without an ISHMS (baseline) and one simulating flying with an ISHMS (ISHMS). In order to define the structure monitored, quantify the material properties, and crack growth associated with that structure, a specific aircraft had to be chosen for the simulations and the CAF A-37 was selected.

5.3.1 Simulation Inputs. The simulations created were greatly simplified, however, since the same assumptions were made for both the baseline and ISHMS simulations, basic comparative conclusions could be made between the two simulations. Both simulations simulated a single edge crack beginning at some specified length growing towards a critical length in one particular FCL on the A-37. The FCL selected for the simulation was the number one FCL identified by the point of highest stress in the A-37 wing. The Walker Fatigue crack growth model was used to simulate crack growth. The material properties input into the model were the average properties for the Al 7075-T6 material of the FCL. The modeled input stresses

were generated from the average mission profile stresses from the fighter spectra from MIL-A-8866. The initial crack length used was calculated from 5000 hour growth of the largest crack size undetectable by human sight. The critical crack length was calculated from the highest possible stress on the FCL with a crack length that would cause residual strength below the peak stress. While most other inputs to the model were averages, the critical crack length modeled the worst case. The probability of detection for the maintenance inspections was assumed to be 97%. Whereas the probability of detection for the ISHMS was assumed to be 99.9%. The probability of detection for the ISHMS encompassed both the system reliability and accuracy.

5.3.2 Final Comments on Benefit Analysis. A comparative analysis between the two simulations run with the inputs described in the section previous showed that an ISHMS may provide benefit over the current status quo with respect to an improvement in safety, lower number of failures per million flight hours, and cost, decreased total number of inspections. The cost benefit only considered the total number of inspections performed between the two simulations and assumed the inspections performed in the two simulations were identical. Of course, even given these assumptions, a cost benefit would only be realized if the life-cycle costs of the ISHMS were less than costs savings from reduced inspections over the life of the aging aircraft. The simulations assumed one crack growing in one FCL. In reality, an ISHMS will need to monitor multiple FCLs with potentially multiple cracks in each FCL. In this case, the realized benefits would most likely be lower than the benefits demonstrated with the simulations. Additionally, the probability of detection for the ISHMS may be lower than that assumed in the simulation given a suite of sensors attempting to accurately detect surface and subsurface cracks growing in multiple directions. This lower probability of detection would lower the potential safety benefit. The true benefit will only be known given a specific implementation of an ISHMS on a specific aging aircraft fleet for a specific lifetime in flight hours.

The generic system definition of an ISHMS for aging aircraft developed with this thesis lays the groundwork for future development and research efforts in this field. This thesis also determined that an ISHMS for aging aircraft will likely provide a benefit with respect to cost and safety. However, much more work needs to be done with respect to the problem of ISHMS and applying the SE process for developing the right ISHMS for aging aircraft.

5.4 Recommendations for Further Research

5.4.1 Continuation of SE Process. Due to multiple constraints, this thesis scoped the SE process developed to not include physical architectures and system design. Future SE efforts should continue the process developed here to include physical architectures and system design. After the process is continued, technical feasibility could be determined. Questions to be answered could include: Does the technology exist to realize safety and/or cost benefits? How many FCLs and/or sensors are necessary for system design? Is installation of the ISHMS technically feasible? Can the ISHMS be effectively integrated with aircraft systems such as GPS and aircraft power?

5.4.2 ISHMS Concept. This thesis assumed that the ISHMS would monitor actual structural damage of the aircraft and most likely alert the aircraft crew of the impending failures. The ISHMS could be designed to monitor aircraft use such as loads, stresses, cycles, and flight hours, for instance. Inputting these monitored inputs into a model, tailored inspection criteria could be developed for each individual aircraft tail number. This method would require accurate models that would first rely on simulation models that would be continually refined as historical data is gained. The models would estimate probable structural damage which would have to be verified with maintenance inspections. Current efforts in structural health monitoring focus on monitoring damage as was done in this thesis. Research needs to be done to determine the optimal implementation of an ISHMS. Should an ISHMS monitor

damage, monitor aircraft use and predict damage, or some combination of monitoring damage and use for a more complete picture of aircraft structural health?

5.4.3 Cost Benefit of ISHMS. The benefit analysis performed in this thesis only considered reduced number of inspections and it assumed all inspections were identical. More detailed analysis of the cost benefit of an ISHMS could be performed considering a larger suite of sensors monitoring multiple FCLs simultaneously. The detailed analysis should attempt to quantify the maintenance cost savings realized for an ISHMS that achieves the same flight safety as the baseline configuration. Detailed life-cycle costs estimates would need to be calculated to compare to the maintenance cost savings estimated to generate a true cost savings over the life of the ISHMS. Since the maintenance cost savings will depend on how the user will implement maintenance changes with respect to the system, multiple estimates of costs savings could be calculated with respect to different user system implementations.

5.4.4 ISHMS Impact on Maintenance. Assuming the development and installation of an ISHMS on aging aircraft occurs in the future, research efforts should focus on the potential impacts to maintenance schedules and operations. Depending on the user's implementation, the ISHMS may significantly reduce or eliminate time-based scheduled inspections and subsequently move towards a tailored inspection schedule for individual aircraft tail numbers. What impact would such a shift in maintenance philosophy have on maintenance manning and operations? Will an ISHMS increase the number of unscheduled maintenance actions? These questions are just a few of the possible questions that could be answered by a detailed investigation into the ISHMS effects on aircraft maintenance.

Appendix A. Matlab Code

This appendix contains the Matlab® code for both the baseline simulation and the ISHMS simulation.

A.1 Baseline Code

Listing A.1: Here is the Matlab® code used for the baseline simulation. (appendix1/baseline.m)

```
clear;
clc;
Inspection_Counter = 0;                                          % ...
   Tracks number of inspections occurring during all trials
C = 0.13E-7;
F = 1.1;
n = 2.791;
m = .65;
Delta_sigma = 20152;
Stress_Ratio = 0;
new_length = 0.0079;
initial_length = 0.02589371;
crack_critical = 0.4781;
Total_Flight_Hours = 0;
trial_hours = 0;

for i=1:1:1000;                                                   % ...
   Number of trials
    Total_Failures = 0;
    for j=1:13;
        Trial_Failure = 0;
        crack_length = initial_length;                            % ...
           Initial crack length of 0.008 inches
        Trial_Failure = 0;                                        % ...
           Changes to one when a trial failure occurs
        t = 0;                                                    % ...
           Initialize flight hour counter to zero
        Inspection_Time = 0;                                      % ...
           Counter tracking time between inspections
        while and(Trial_Failure == 0, t <= 5000)                  % ...
           No trial failures and time less than 5000 flight hours
            if Inspection_Time == 300
                p = rand(1);                                      % ...
                   Rand detection probability
                if p > .03                                        % ...
                   Check to see if crack is detected  (97% are ...
                   detected)
                    crack_length = new_length;                    % ...
                       If crack detected, resets length to new ...
                       length
```

```
                    else
                        crack_length = crack_length;
                    end
                    Inspection_Time = 0;                               % ...
                       Resets inspection time
                    Inspection_Counter = Inspection_Counter + 1;    % ...
                       Increments inspection counter
                end
                crack_growth = (C * ((F*Delta_sigma*(pi()*crack_length...
                   )^.5)/((1-Stress_Ratio)^(1-n)))^m);   %Crack Growth...
                    Equation
                crack_length = crack_length + (crack_growth*100); ...
                           % Crack growth
                if crack_length > crack_critical                       % ...
                   Checks to see if crack is greater than critical ...
                   length
                    Trial_Failure = 1;
                    Total_Failures = Total_Failures + 1;
                end
                trial_hours = t;
                t = t + 1;                                             % ...
                   Increment time
                Inspection_Time = Inspection_Time + 1;                 % ...
                   Increment inspection time
            end
            Total_Flight_Hours = Total_Flight_Hours + trial_hours;
        end
        Results(i) = [Total_Failures];                                 % ...
           Builds array with failure data from all trials
    end

    Average = mean(Results)
    Std_Dev = std(Results)
    Failures = sum(Results)
    max = max(Results)
    Inspection_Counter
    Failures_Mln_Hours = (Failures/Total_Flight_Hours)*1000000
```

A.2 ISHMS Code

Listing A.2: Here is the Matlab® code used for the ISHMS simulation. (appendix1/ISHMS.m)

```
clear;
clc;
Inspection_Counter = 0;  % Tracks number of inspections occurring ...
    during all trials
C = 0.13E-7;
F = 1.1;
n = 2.791;
m = .65;
Delta_sigma = 20152;
Stress_Ratio = 0;
new_length = 0.0079;
initial_length = 0.02589371;
crack_critical = 0.4781;
Total_Flight_Hours = 0;
trial_hours = 0;

for i=1:1:1000;                                                  % ...
    Number of trials
     Total_Failures = 0;
     for j=1:1:13;                                               % ...
         Number of Aircraft in fleet
          crack_length = initial_length; ...
                                             % Initialize crack length
          Trial_Failure = 0; ...
                                                        % Changes to ...
              one when a trial failure occurs
          t = 0; ...
                                                                   % ...
              Initialize flight hour counter to zero
          Inspection_Time = 0; ...
                                                      % Counter ...
              tracking time between inspections
          while and(Trial_Failure == 0, t <= 5000) ...
                                    % No trial failures and time less ...
              than 5000 flight hours
               if Inspection_Time == 700                          % ...
                   Sets inspection timeframe
                    p = rand(1);
                    if p > .03 ...
                                                                 % ...
                        Random number draw to see if crack is detected...
                         (97% detected)
                         crack_length = new_length;
                    end
                    Inspection_Time = 0;
                    Inspection_Counter = Inspection_Counter + 1;
               end
```

```
                crack_growth = (C * ((F*Delta_sigma*(pi()*crack_length...
                    )^.5)/((1-Stress_Ratio)^(1-n)))^m);   % Crack ...
                    growth equation
                crack_length = crack_length + (crack_growth*100); ...
                           % Crack growth equation cont.
                if crack_length > .9*crack_critical ...
                                        % ISHMS checks to see if ...
                    crack is greater than 90% of critical
                    p1 = rand(1);
                    if p1 > .999
                        Trial_Failure = 1;
                        Total_Failures = Total_Failures + 1;
                    else
                        crack_length = new_length;
                        Inspection_Time = 0;
                        Inspection_Counter = Inspection_Counter + 1;
                    end
                end
                trial_hours = t;
                t = t + 1;
                Inspection_Time = Inspection_Time + 1;
            end
            Total_Flight_Hours = Total_Flight_Hours + trial_hours;
        end
        Results(i) = [Total_Failures];
    end

    Average = mean(Results)
    Std_Dev = std(Results)
    Failures = sum(Results)
    Inspection_Counter
    Failures_Mln_Hours = (Failures/Total_Flight_Hours)*1E6
    Max_Failures = max(Results)
```

Functional Activities Listed in Alphabetical Order

Determine Aircraft Inspection Intervals - an ISHMS may be able to reduce the inspection burden, but not eliminate the need for some inspections. As such, one of the potential benefits of an ISHMS come from cost avoidance of inspection and maintenance costs.

Determine Aircraft Structural Condition - once an aircraft's ISHMS data has been collected and analyzed, then the aircraft's structural condition should be determined.

Determine Available Sensor Technology - sensor selection for each FCL will be limited by the technology that is available in the market; either existing or emerging technology.

Determine Data Analysis Requirements - define the purposes of the data, the methodology for any calculations required, organizations responsible for conducting, verifying, and validating the analysis, etc.

Determine Data Processing Requirements - manipulating the ISHMS sensor data such that it would be suitable to conduct the appropriate analysis.

Determine Data Requirements - design aspects relating to data format, data storage, data filtering, etc.

Determine Data Storage Requirements - data from the sensors must be stored somewhere. Several data characteristics will determine the storage requirements needed for the ISHMS.

Determine Desired ISHMS Accuracy - this refers to the desired level of confidence of the ISHMS in detecting failures on structural members.

Determine Failure Mode to be Detected - each sensor must be tailored to the specific fatigue location that it will be monitoring.

Determine ISHMS Calibration Requirements - validation and verification of the ISHMS.

Determine ISHMS Maintenance Requirements - details about system sustainment, calibration, maintenance and the respective organizations or systems responsible of providing the maintenance services.

Determine ISHMS Operational Requirements - this is the activity in which stakeholders express their expectations of how the ISHMS should operate and what services it should provide. More detailed information will most likely translate into a more satisfied customer.

Determine ISHMS Reliability - calculations made to determine the expected operational availability of the system. Redundant systems are usually more reliable, but also more complex and costly.

Determine ISHMS Routine and Preventive Maintenance Procedures - procedures for the sustainment and maintenance of the ISHMS. Includes repairing the ISHMS and keeping it fully operational.

Determine Monitoring Requirements - design aspects relating to the placement, quantity, and sensor type selection. These characteristics will define to a great extent the physical systems necessary to build an ISHMS that would satisfy stakeholders.

Determine Operating Environment - environmental factors, both internal and external, may influence the sensor selection for each critical location. Examples of environmental factors are humidity, vibration, temperature, etc.

Determine Safety of Flight - SOF is measured in statistical terms. The ISHMS should be able to at least maintain the level of SOF that is currently attained with the inspections. It would probably take into consideration several factors to include the reliability of the ISHMS.

Determine Sensor Locations - establishing the placement of the sensors will be a critical design feature of the ISHMS.

Determine Sensor Properties Requirements - each individual sensor must be tailored to the specific fatigue critical location that it will be monitoring. Sensor types may differ due to differences in failure modes, loading stresses, environmental factors among other issues that may vary among fatigue critical locations. Response time must also be considered as a potential driving requirement to satisfy the near-real time user requirement.

Determine Sensor Quantity - answers how many sensros will be needed. Obviously this activity involves trade-offs between costs and robustness of the system. Ideally, more sensors will do a better monitoring job; however an increasing number of sensors will increase the cost and complexity of the ISHMS.

Determine Sensor Selection - the activity of matching a specific sensor to an FCL.

Identify Fatigue Critical Locations - weakened areas in an aircraft's structural members whose failure can lead to a catastrophic event. Usually, historical failure trends could be used to identify some FCLs on an airframe.

Identify ISHMS Requirements - This is the context diagram for the ISHMS architectures and defines the boundaries of the subsequent decompositions. Notice the purpose of the architectures is to establish a systematic approach to generate or identify stakeholder requirements. Engineers shall incorporate these requirements into the system design to ensure stakeholder satisfaction when the final ISHMS solution is delivered.

Identify Other Critical Locations - do not limit the research of catastrophic failure to only FCLs. Include in the analysis other components that may be beneficial to monitor with the ISHMS.

Make Informed Fleet-wide Decisions - this refers to the thesis scenario in which commanders may be able to switch aircraft tail numbers in order to maintain an even wear and tear among aircrafts organization-wide according to ISHMS information.

Prioritize Critical Locations - a risk management analysis would probably be most suitable in accomplishing this activity. Monitoring Emphasis should be placed on thos FCLs that have a higher risk of catastrophic failure.

Provide Necessary Aircraft Maintenance - plan follow-on repair/maintenance procedures based on the ISHMS assessment and any additional inspections. In other

words, an ISHMS may help in the planning and scheduling of aircraft maintenance operations.

ICOMs Listed in Alphabetical Order

Aircraft Design Characteristics - design features that make an aircraft design unique or different. Can also be thought of as an aircraft implementation. Includes criteria such as weight and balance limits, electronic- magnetic interference (EMI) constraints, aircraft power limits, etc.

Aircraft Inspection Intervals - the amount of time (often measured in flight hours) between required aircraft inspections. These inspections are often required as part of the ASIP and SLEP, or any other program designed to extend the life of an aircraft beyond the original design life.

Aircraft Maintainers - flightline personnel dedicated to repairing or reconditioning aircraft to an operational status.

Aircraft Maintenance Report - report generated to log the maintenance performed on an aircraft. This data may be used to identify new FCLs.

Aircraft Structural Health Condition - the resulting assessment from the ISHMS data analysis combined with any other inspections performed.

Analyzed Data - the results or outcomes of the ISHMS data analysis.

Bandwidth Availability - the amount of ISHMS sensorial data that can be passed along a communications channel in a given period of time.
Assessment of the damage the aircraft specimen currently has prior to test.

Calibrated Instrument - verification and validation that the ISHMS is making accurate measurements.

Cost / Budget - the total sum of money allocated for a particular purpose or period of time.

Critical Locations Priority List - a list of critical locations in order of importance. The order of importance will most likely be determined by factors such as frequency of occurrence and potential for damage (Risk Management).

Current Fleet Status Report - one of the outputs that the ISHMS would be expected to generate. An ISHMS could potentially allow commanders assess their unit's readiness with the click of a button.

Data Acquisition Unit - a hypothetical component that will store sensor data. This mechanism can be performed by an automated system or by some human organization, or

a combination of both.

Data Format - the computer language and structure in which the data must be written. This may be important in preventing software compatibility issues, especially if the ISHMS needs to interact with legacy systems.

Data from Sensors - raw signal inputs coming from each ISHMS sensor.

Engineering Analysis - scientific studies performed to determine ISHMS design characteristics.

Engineers - are a subset of stakeholders. May be either contractors, military or government civilian. Probably composed of a multi-disciplinary mixture of mechanical, aeronautical, electrical, computer and system engineers. Perhaps some scientists may also be included in this category (i.e., experts in ceramics, computer networks, maintainers, etc.)

Environmental Factors - a combination of surrounding conditions that may affect the state of the systems that compose the ISHMS. Environmental factors can be either internal or external. Internal factors refer to the localized environmental factors within the airframe structure. For example, a fatigue critical location that needs to be monitored may be submerged in hydraulic fluid, or may experience a high vibration frequency and

temperature due to its proximity to the engine, etc. External factors refer to the operational environment area. For example, proximity to sea water may promote corrosion problems, a dusty environment may require a more robust sensor, extremely cold temperatures may affect the electronic properties of the sensor, etc. Failure Mode - the most probable failure mode or modes that the FCL may experience (i.e., corrosion, shear or load stress, vibration, etc.)

Fatigue Critical Locations - areas where structural members are more vulnerable to damage that can lead to catastrophic failure. Each FCL may have one or multiple failure modes. Failure may be due to crack growth, corrosion, fatigue stress, load stress, etc.

Flight Profile - refers to the severity or level of aggresiveness with wich the aircraft is being flown. Usually this will depend on the aircraft's role or operational mission.

Historical Data - information based on a record of previous events. In the case of the development of an ISHMS this may include maintenance records, accident reports and any other aircraft information that has been logged through time. Emphasis should be placed on identifying trends of repetitive safety issues.

ISHMS Design Requirements - a compilation of all

stakeholders' requirements. This will help constraint the design space (i.e., the number of acceptable ISHMS solutions), thus simplifying the development phase.

List of Sensors Available - the list would show the range of sensor that have the potential of being part of an ISHMS.

Maintenance Practices - the rigor or lack of efficient maintenance practices will most likely have an impact of the number and priority of potential structural problematic areas.

Maintenance Procedures - should be included early on the design phase as part of the lifecycle design requirements. Inevitably, some components of the ISHMS will fail and will have to be replaced. Consideration of maintenance procedures will prevent the creation of a remedy (i.e., ISHMS) that is worst than the cause (i.e., inspections).

Operating Environment - external and internal environmental factors that affect sensor selection

Operational Aircraft - an aircraft 100% ready for operational use.

Other Critical Locations - these are non-FCL locations that historically have experienced high failure rates and

have the potential to capitalize on the implementation of an ISHMS.

Other Inspections - inspections required to have a complete assessment of an aircraft's condition. Other inspections may be prompted as a result of ISHMS data analysis or may be required because of ISHMS deficiencies.

Policies & Regulations - established principles, rules, or laws designed to control or govern conducts or procedures.

Probability of Detection - the ability of the ISHMS to detect a failure only when there is actually a potential failure or not detecting failure when there is none. This relates to the probability concept of confidence level (false-false and false-true).

Processed Data - raw data that has been converted. Examples are time stamping the data for synchornization purposes, sorting data, filtering the data, etc.

Research Practices - the skills, knowledge and professionalism of whoever is conducting a scientific research or analysis may have an impact on the final outcome.

Safety of Flight - the level of safety expected that the ISHMS

must sustain for aircraft operation. Most likely will be established by the user and is usually measured in statistical or probabilistic terms.

Sensor Quantity - the number of sensors that the ISHMS will require to satisfy stakeholder's needs.

Sensor Selection - a match of a sensor tailored to the FCL it will monitor.

Stakeholders - anyone who has a share or an interest in the ISHMS. Usually includes developers, designers, users, contractors, etc.

Stakeholder's Inputs - preferences established by the stakeholders. Extreme care must be taken to properly justify all stakeholders' inputs. The ISHMS design must not be influenced by an individual's will nor by group think.

Stored Data - data that has been stored in the data acquisition unit.

Technology - defined as the practical application of science to commercial or industrial purposes. Technology can be classified into emerging or existing. Existing technology is usually more readily available and cheaper. Existing technology usually needs to be validated before integrating it into a design.

Upper Management - a subset of the stakeholders that have an authority beyond normal. These people may have the influence to implement major decisions that have the potential to effect changes on other systems or organizations.

This appendix contains the Performance Indices for the requirements Weighted Objectives Hierarchy. First, the cost indices are presented, followed by the performance indices and finally the schedule index.

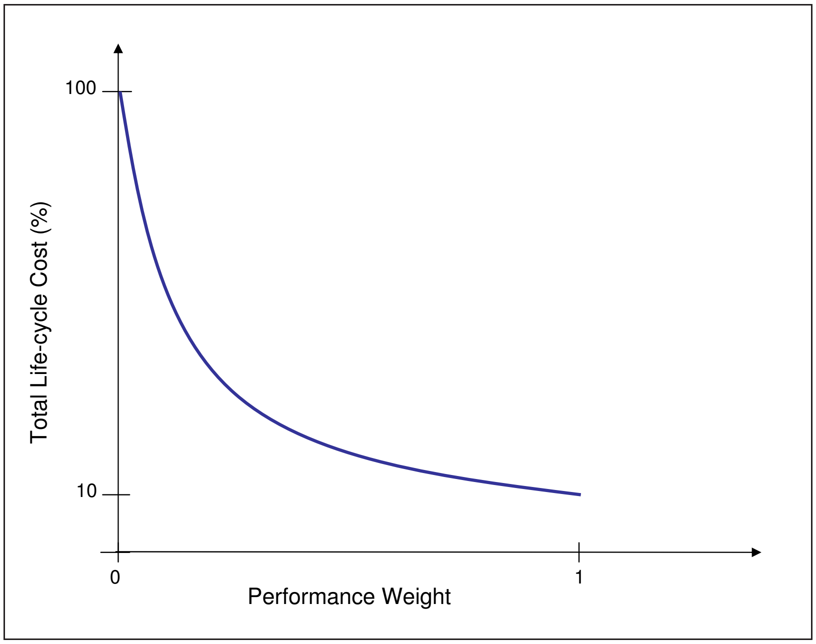

Figure C.1: Development Cost Performance Index

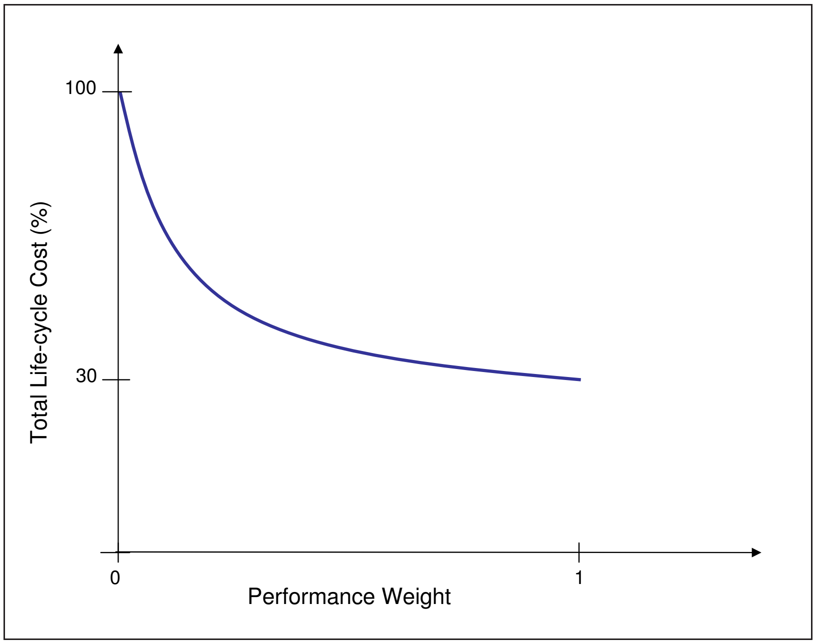

Figure C.2: Acquisition Cost Performance Index

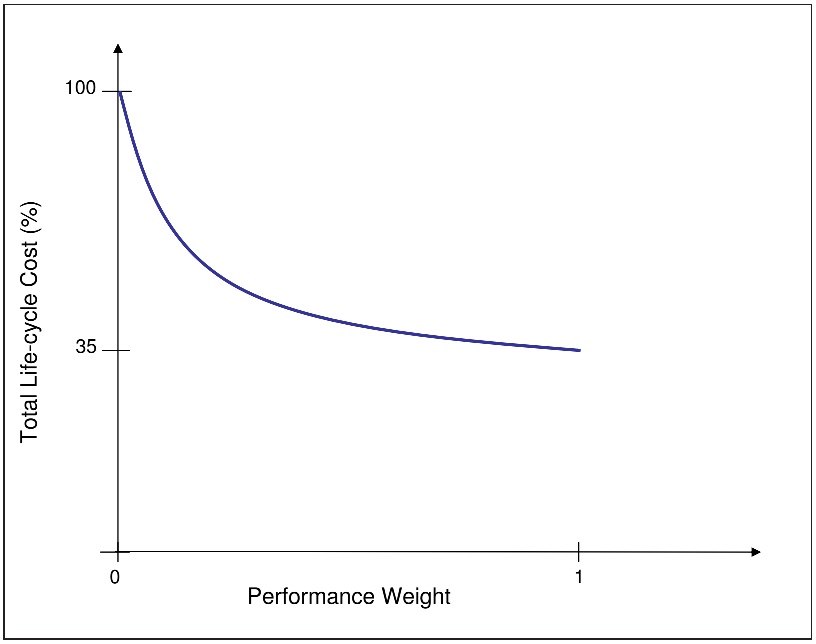

Figure C.3: Installation Cost Performance Index

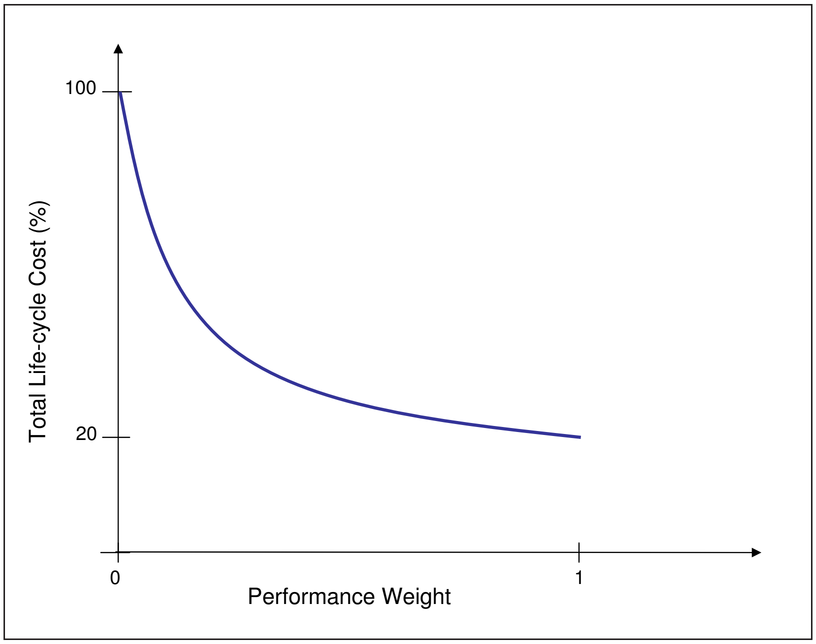

Figure C.4: Operation Cost Performance Index

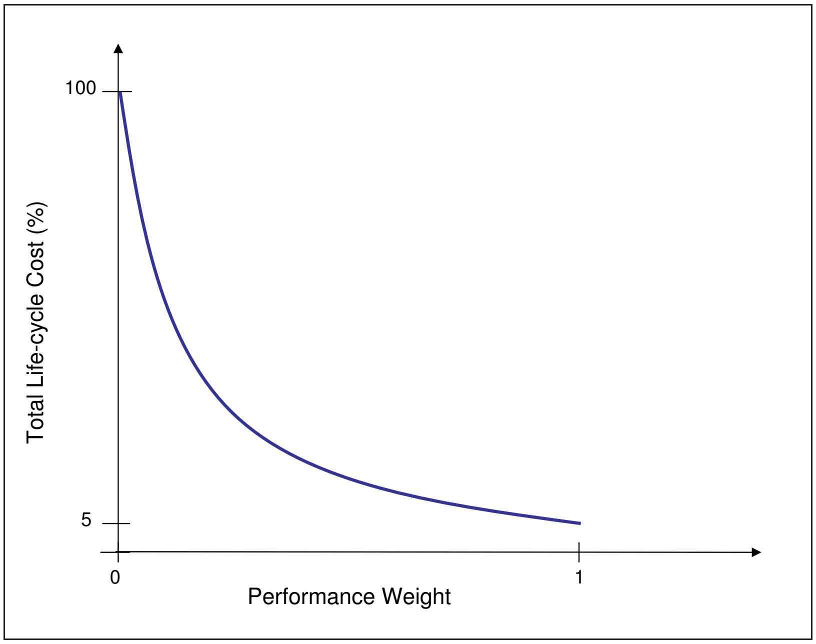

Figure C.5: Disposal Cost Performance Index

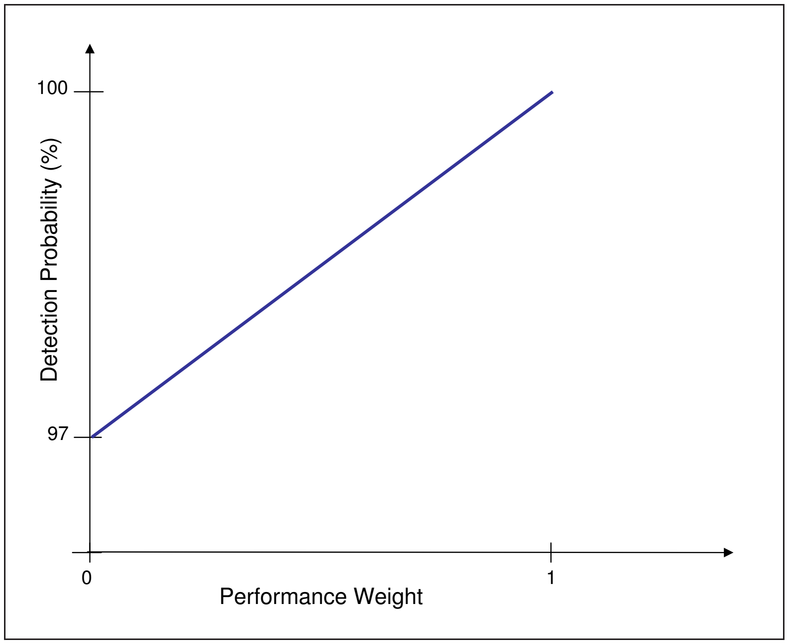

Figure C.6: Probability Of Detection Performance Index

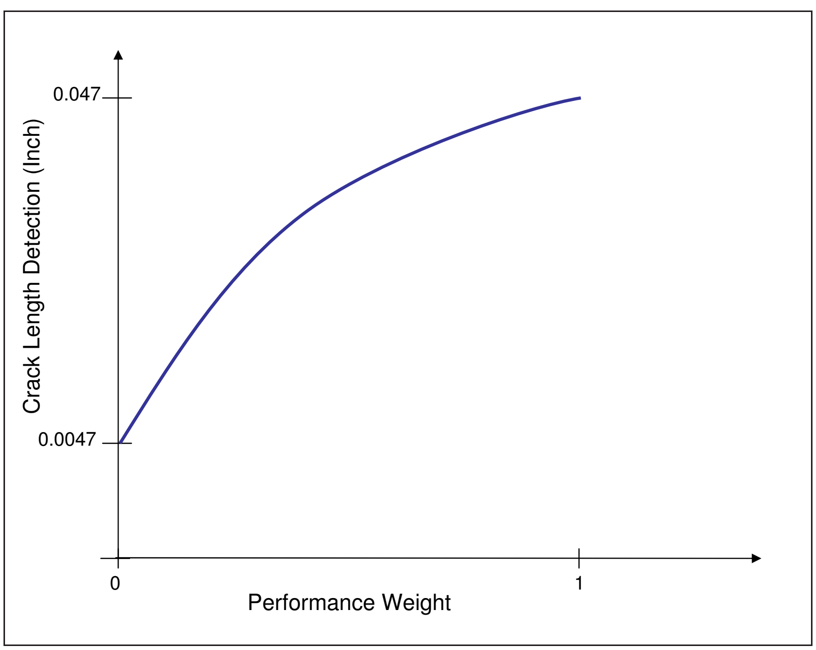

Figure C.7: Crack Length Detection Performance Index

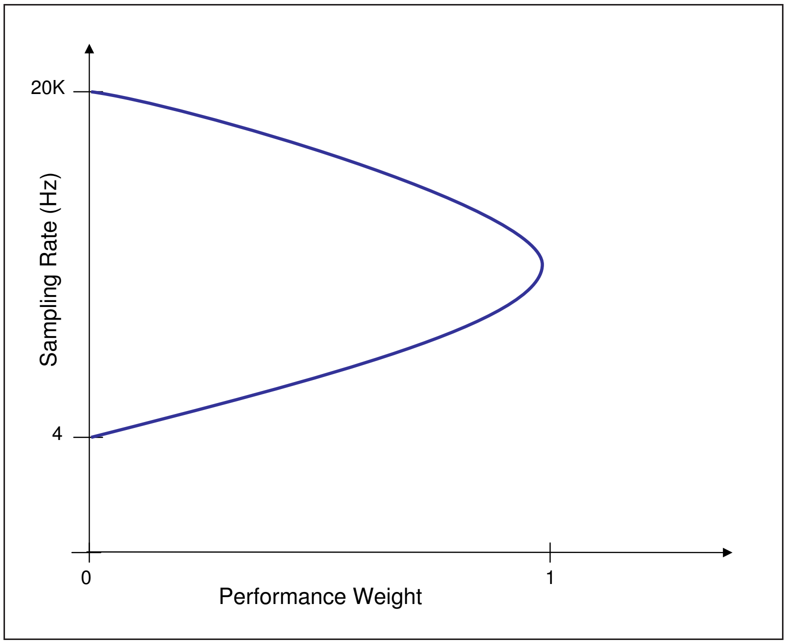

Figure C.8: Sampling Rate Performance Index

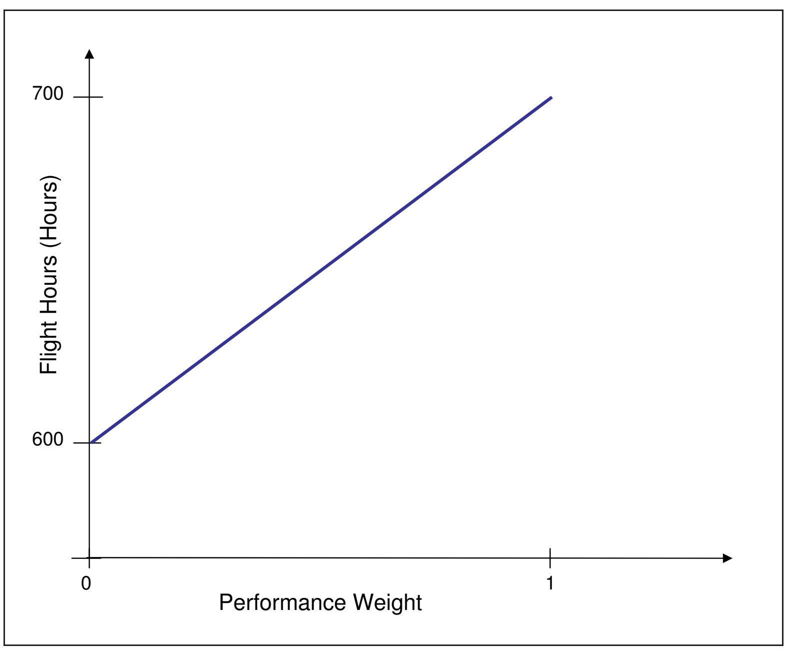

Figure C.9: Data Storage Performance Index

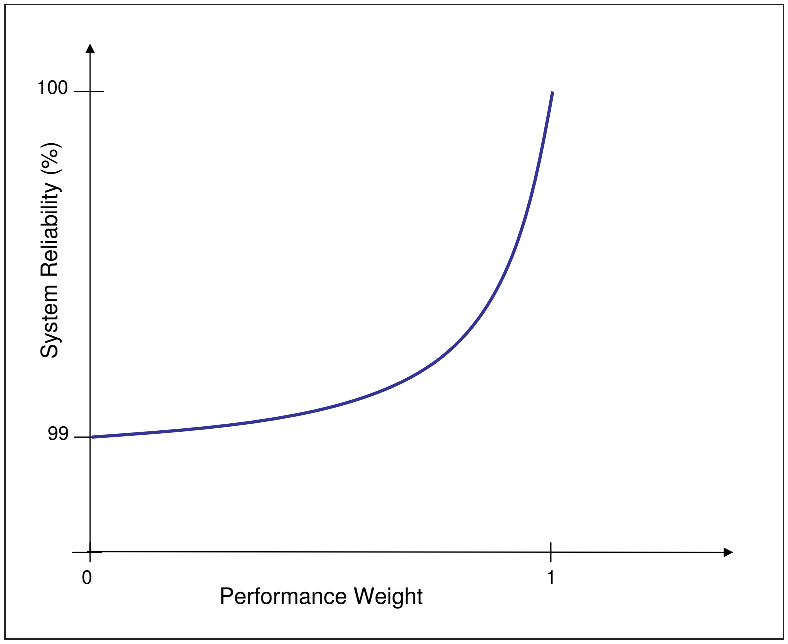

Figure C.10: System Reliability Performance Index

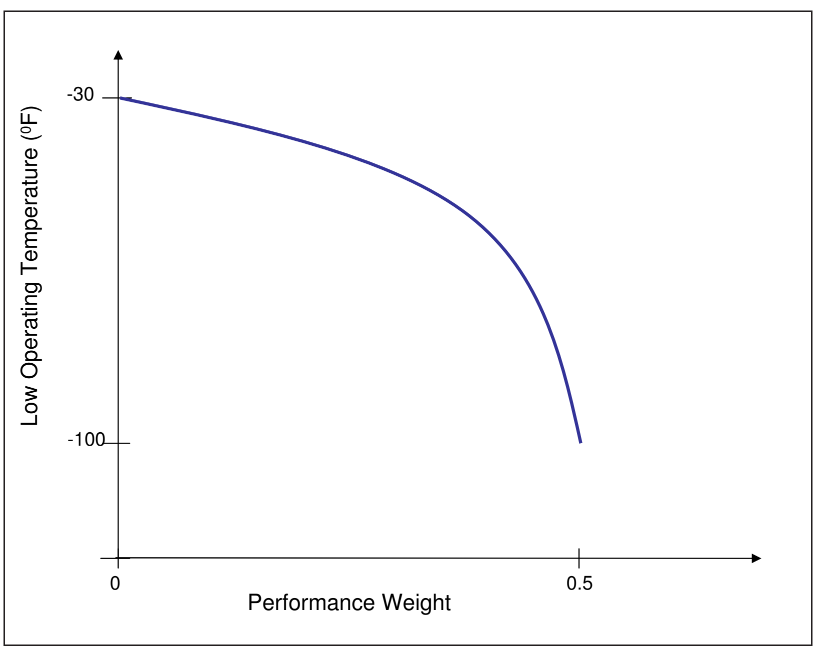

Figure C.11: Low Operating Temperature Performance Index

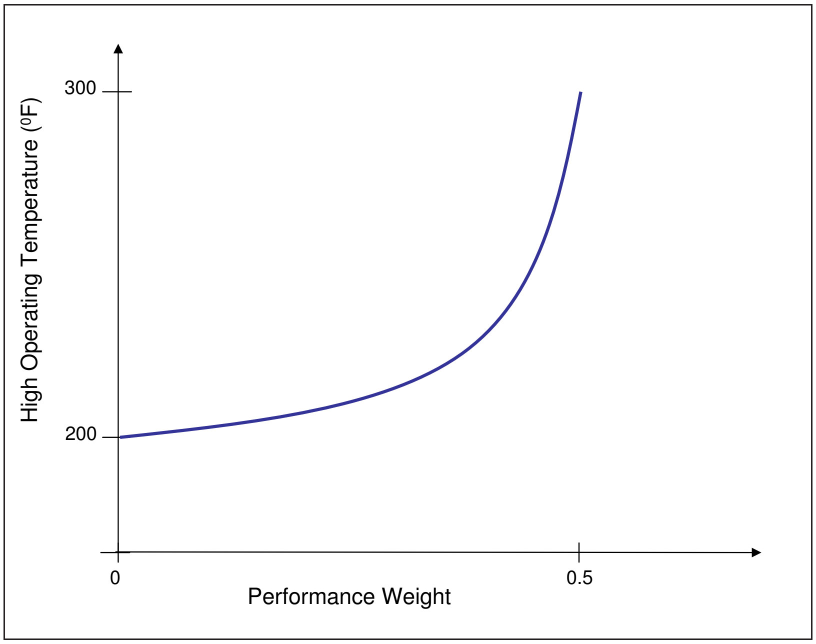

Figure C.12: High Operating Temperature Performance Index

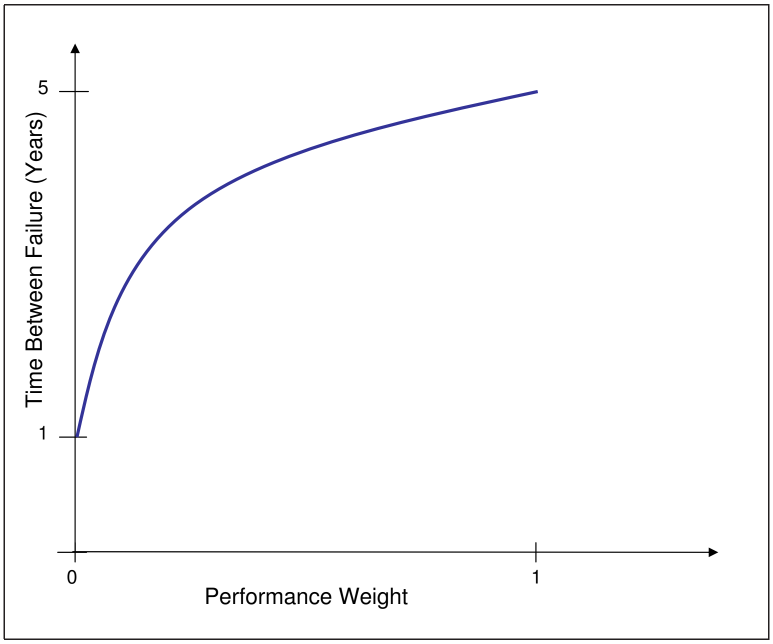

Figure C.13: Mean Time Between Failure Performance Index

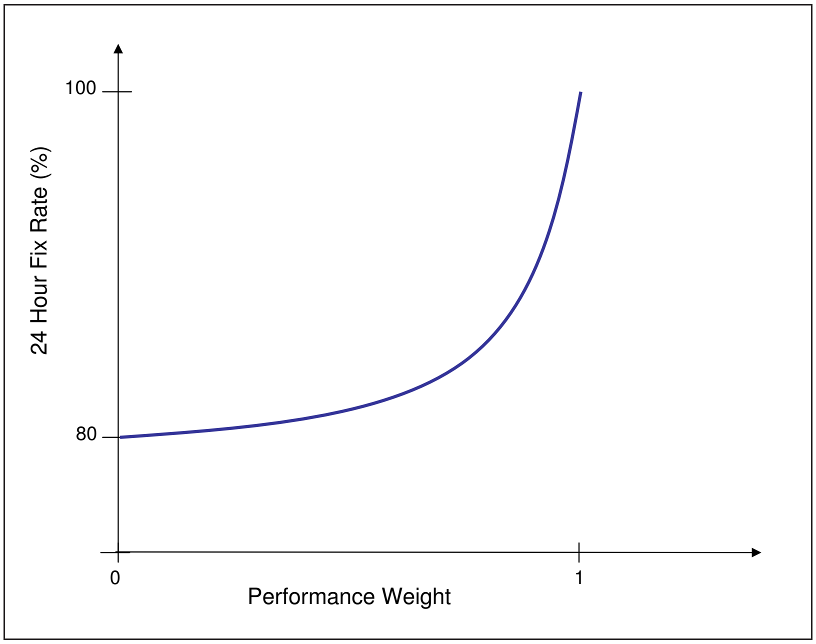

Figure C.14: 24 Hour Fix Rate Performance Index

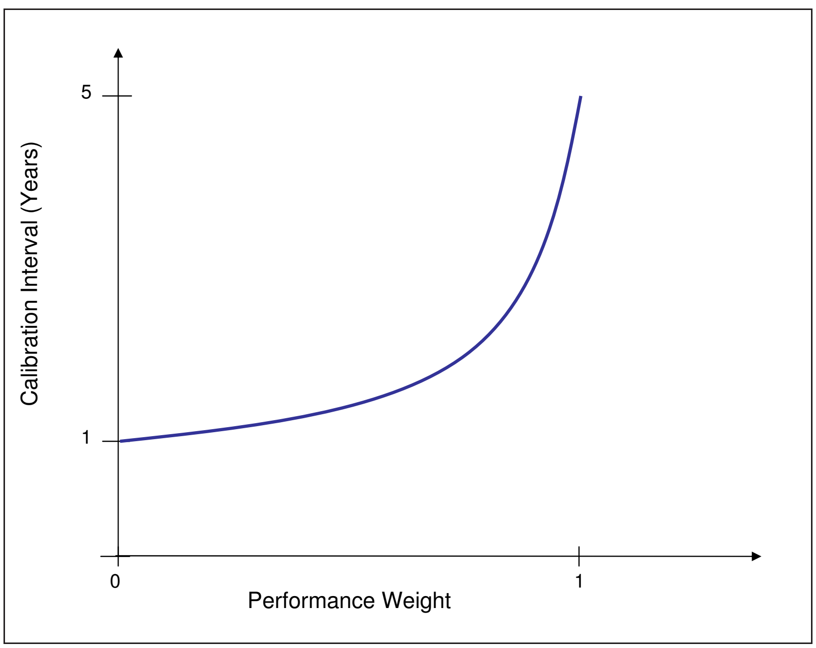

Figure C.15: Calibration Interval Performance Index

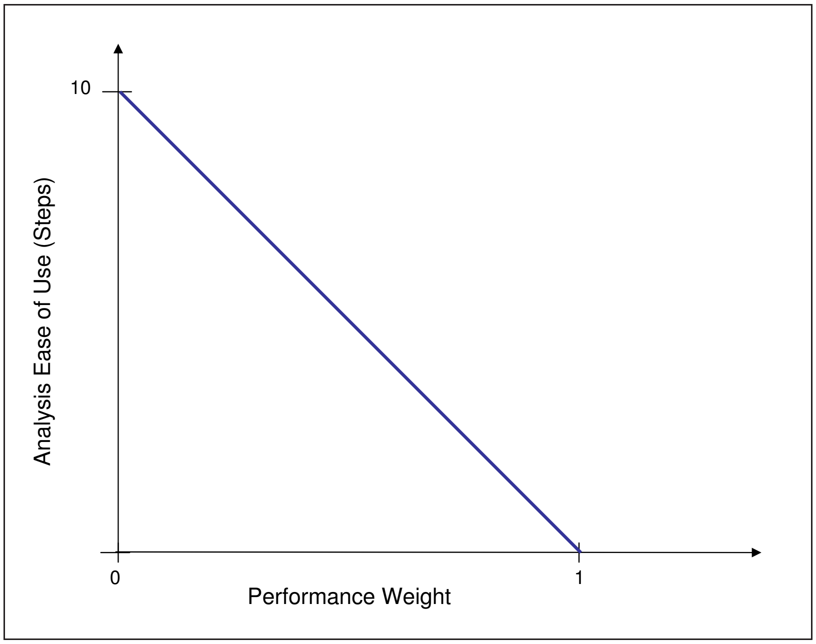

Figure C.16: Analysis Ease of Use Performance Index

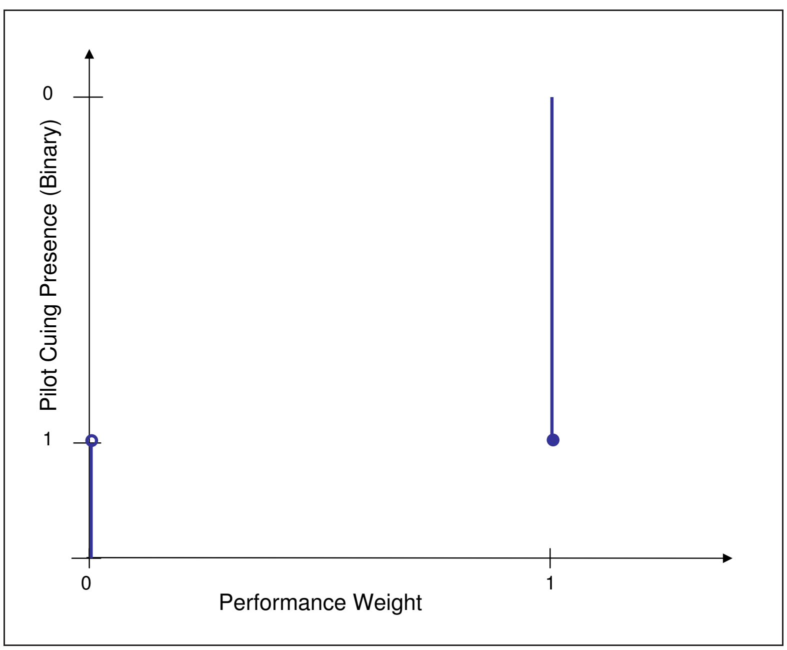

Figure C.17: Pilot Cuing Performance Index

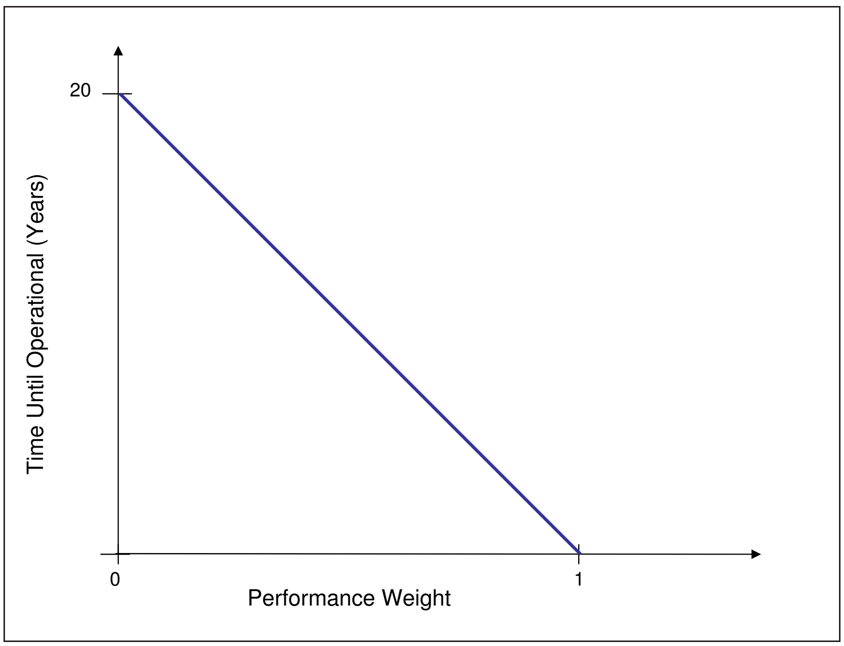

Figure C.18: Schedule Performance Index

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